

COPY

2

MEMORANDUM REPORT BRL-MR-3880

BRL

AD-A229 674

CURRENT SIMULATION METHODS IN
MILITARY SYSTEMS VULNERABILITY ASSESSMENT

PAUL H. DEITZ
MICHAEL W. STARKS
JILL H. SMITH
AIVARS OZOLINS

NOVEMBER 1990

DTIC
ELECTE
DEC 11 1990
S B D

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

NOTICES

Destroy this report when it is no longer needed. DO NOT return it to the originator.

Additional copies of this report may be obtained from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.

The findings of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

The use of trade names or manufacturers' names in this report does not constitute indorsement of any commercial product.

UNCLASSIFIED

REPORT DOCUMENTATION PAGE			Form Approved OMB No 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE November 1990		3. REPORT TYPE AND DATES COVERED Final, Jun - Aug 90
4. TITLE AND SUBTITLE Current Simulation Methods in Military Systems Vulnerability Assessment			5. FUNDING NUMBERS IL162618AH80 DA303335	
6. AUTHOR(S) Paul H. Deitz, Michael W. Starks, Jill H. Smith, Aivars Ozolins				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Ballistic Research Laboratory ATTN: SLCBR-DD-T Aberdeen Proving Ground, MD 21005-5066			10. SPONSORING/MONITORING AGENCY REPORT NUMBER BRL-MR-3880	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for Public Release; Distribution is Unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Due chiefly to the requirements and opportunities of Live-Fire Testing during the past five years, substantial efforts have been expended by the Ballistic Research Laboratory (BRL) to improve the state of armored vehicle vulnerability modeling. In order to mirror field observables, the existing point-burst methodology was extended to include the principal sources of stochasticism intrinsic to physical damage processes. This has led to the ability to predict the probability of specific damage states occurring on a shot-by-shot basis. Such damage characterization, when calibrated with Live-Fire experiments, represents for the first time an analytical tool that approaches a "first principles" vulnerability model. What emerges now is a hierarchy of vulnerability models. At the low end are codes capable of estimating warhead perforation (including residuals) into armored vehicle ballistic hulls and turrets. At the next level is the so-called Compartment-Code methodology. With this level of modeling, all LoFs are related to main-penetrator residuals by lumped-parameter relations. At the high end exist the aforementioned stochastic methods. We further propose that this generic strategy be tailored to all classes of threat/target interactions.				
14. SUBJECT TERMS vulnerability lethality models			15. NUMBER OF PAGES 46	
Behind-Armor-Debris BRL-CAD SQUASH			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED		18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED		19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED
			20. LIMITATION OF ABSTRACT SAR	

NSN 7540-01-280-5500

UNCLASSIFIEDStandard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

INTENTIONALLY LEFT BLANK.

TABLE OF CONTENTS

	Page
LIST OF ILLUSTRATIONS	v
1. INTRODUCTION	2
2. USES OF V/L MODELS	5
3. CRITICISM OF V/L PRACTICE	6
4. V/L FRAMEWORK	8
5. SQuASH AS KEY MEMBER	12
5.1 Technical Improvements Provided by SQuASH	13
5.1.1 Stochasticism	13
5.1.2 Physics for Kinetic Energy (KE) Penetrators	13
5.1.3 Truncation of Intermediate Results	13
5.1.4 Improved Realism	13
5.2 Recent SQuASH Extensions	13
5.2.1 Batch Computation	13
5.2.2 Support for Degraded States	14
5.2.3 Support for SPARC Calculations	14
5.2.4 Derivation of Lower-Level Models	15
5.3 Validation of SQuASH	15
6. FUTURE DIRECTIONS IN V/I MODELING	17
7. VLD MASTER PLAN	18
8. SUMMARY AND CONCLUSIONS	20
DISTRIBUTION LIST	21



Accession For	
NTIS GRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

INTENTIONALLY LEFT BLANK.

LIST OF ILLUSTRATIONS

Figure	Page
1. Plot of VLD Computing Capability <i>versus</i> Year.....	4
2. Four Spaces of Vulnerability	9
3. Mobility LoF vs Profile Hole Diameter.....	12
4. Predicted M/F LoF vs Profile Hole Diameter	16
5. Predicted M/F LoFs vs Number of Critical Components Killed	16

INTENTIONALLY LEFT BLANK.

CURRENT SIMULATION METHODS IN MILITARY SYSTEMS VULNERABILITY ASSESSMENT

Dr. Paul H. Deitz
Dr. Michael W. Starks
Ms. Jill H. Smith
Mr. Aivars Ozolins

US Army Ballistic Research Laboratory
Vulnerability/Lethality Division
ATTN: SLCBR-VL-V (P. Deitz)
Aberdeen Proving Ground, MD 21005-5088

ABSTRACT

Due chiefly to the requirements and opportunities of Live-Fire Testing during the past five years, substantial efforts have been expended by the Ballistic Research Laboratory (BRL) to improve the state of armored-vehicle vulnerability modeling. In order to mirror field observables, the existing point-burst methodology was extended to include the principal sources of stochasticism intrinsic to physical damage processes. This has led to the ability to predict the probability of specific damage states occurring on a shot-by-shot basis. Such damage characterization, when calibrated with Live-Fire experiments, represents for the first time an analytical tool that approaches a "first principles" vulnerability model.

Since the development and application of the stochastic point-burst model, called SQuASH, in the Abrams Live-Fire program, further modifications have been implemented. These include:

- Batch mode capability for thousands of hit points
- Support of more robust Degraded States vulnerability metrics in addition to the traditional Loss-of-Function (LoF) values
- Estimation of spare parts requirements and vehicle repair times
- Calculation of lumped-parameter vulnerability relationships for use in the Compartment Model
- Enhancements to provide stochastic simulation of fragmenting munitions

What emerges now is a hierarchy of vulnerability models. At the low end are codes capable of estimating warhead perforation (including residuals) into armored vehicle ballistic hulls and turrets. At the next level is the so-called Compartment-Code methodology. With this level of modeling, all LoFs are related to main-penetrator residuals by lumped-parameter relations. At the high end exist the aforementioned stochastic methods. We further propose that this generic strategy be tailored to all classes of threat/target interactions.

In this paper the various levels of military-systems modeling will be described together with some candidate techniques now available for utilizing the high-resolution models to calibrate the lower-level vulnerability codes.

1. INTRODUCTION

Historians generally credit Gabriel Mouton, the vicar of St. Paul's Church in Lyon, France, with conceptualizing in 1670 the comprehensive system of weights and measures which was to become the metric system. His notion was to utilize units of measure from the physical universe rather than the human body and incorporate a decimal system. Implementation of Mouton's ideas languished for more than a century until the French Revolution of 1789 provided the catalyst for change. A committee of the French Academy of Science recommended in 1791 that the basic unit of length be derived from a measurement of the earth and be equal to 10^{-7} of the distance from the North Pole to the equator. This new "standard" was to become the *metre*. Following a half-decade of effort to resolve a number of technical and political problems involved in the geodesic survey, a formal "prototype metre" was fabricated in 1798 and presented for adoption.

At the outset, the metre was defined in practice by the length of a platinum bar conserved in Paris. About the same time, fifteen iron copies of the prototype were fabricated; one of these copies made its way to the United States and became the standard of measure in this country, serving until 1890. Today the metre is defined not in terms of a mechanical reference but as a multiple of the orange-red line of the spectrum of krypton-86.

We make two observations with respect to standards. First, at any given time the best extant technology provides the *reference* standard—the highest level of accuracy. In the case of the metre, the reference is an *absolute standard by definition*. As technology evolves, the reference standard may be redefined to exploit the increased precision of a new technology or device. Second, at any given time *derivative* standards may be fabricated whose accuracy is traceable to a higher level. The highest-level standards, sometimes called *national reference standards*, are often kept under close supervision and ideal environments; their mass utilization is often not practical due to factors of ruggedness, durability or operational overhead. What emerges is a set of *hierarchical* standards, each appropriate for particular applications, with traceability to the top-level reference.

By analogy, substantial efforts today are being focused by the **Ballistic Research Laboratory (BRL)** on a new generation of precision simulation models. The best of these will constitute *reference standard models* calibrated, to the maximum extent possible, to full-scale field trials. However, unlike the reference standard of length, these reference models will not form absolute standards but rather reflect confidence bounds for accuracy and/or precision traceable by statistical considerations to various measurements. These models will be exercised when their level of accuracy or precision is required; they will also be used to calibrate lower-level codes when greater output detail is not appropriate or possibly when detailed input specification is lacking.

The first vulnerability model developed to support **Armored Fighting Vehicles (AFVs)** was formulated in 1958.¹ Called the Compartment Code, it was experimentally grounded in full-scale tests performed in the US between 1950 and 1954. It was substantially revised based on some 400 anti-tank firings against M47 and M48 tanks in tests performed in Canada in 1959. Called the CARDE Trials,² they established the experimental foundation for essentially the only direct-fire vulnerability model and, by definition, the reference vulnerability code, for the time, as well. The Compartment Model is a relatively unrefined vulnerability code.³ The target is geometrically modeled in relatively low detail.

1. For a historical perspective on vulnerability testing and modeling, see Paul H. Deitz and Aivars Ozolins, *Computer Simulations of the Abrams Live-Fire Field Testing, Proceedings of the XXVII Annual Meeting of the Army Operations Research Symposium*, 12-13 October 1988, Ft. Lee, VA; also Ballistic Research Laboratory Memorandum Report BRL-MR-3755, May 1989.

2. *Tripartite Anti-Tank Trials and Lethality Evaluation, Part I, Canadian Armament Research and Development Establishment*, November 1959.

3. Bradshaw F. Armendt, Jr., *Methods of Assessing Anti-Armor Weapons Lethality*, Working Paper 51 of Subpanel 3 of NATO AC/225, July 1974.

Of the many hundreds of interior components which exist in an actual AFV, only a dozen or so are explicitly analyzed in this model.[‡] Until the past few years, the Compartment Model still served as the reference model for most assessments of direct-fire weapons against AFVs. A number of more refined codes could in principle have displaced the Compartment Model beginning as long as fifteen years ago.

That more refined codes were not developed until recently is due to a series of required resources that only in the past five years have come in to play. Beyond detailed knowledge of warhead/armor interactions, advanced vulnerability computations require support from a diverse set of disciplines. They include:

- **Behind-Armor Debris (BAD) and Component P_{K/H} Methods and Databases:** High-resolution vulnerability codes explicitly estimate all lethal mechanisms and their potential for killing critical components. Only during the past decade have 1] the analytical methods been developed,⁴ 2] the computer-assisted scanning and data-reduction techniques been put in place,^{5,6} and 3] a significant number of warhead/armor pairings been examined⁷ to enable BAD-based methods to be exploited reliably. Similar progress is also advancing knowledge of component-kill susceptibility.⁸
- **BRL-CAD:** As noted above, vulnerability codes are extremely input intensive. Even baseline codes require the explicit representation of three-dimensional solid geometry. The BRL has established a powerful set of tools called BRL-CAD⁹⁻¹² which provide support for the generation, viewing, manipulation and utilization of massive 3-D geometric data bases. Until a few years ago, target descriptions were rarely composed of more than 1500 elements or components. Today some high-resolution descriptions exceed 6000 elements with corresponding ASCII-file sizes in excess of 20 Megabytes. BRL-CAD is now the standard for geometric/material input to vulnerability analyses in the Army and Air Force.

‡ In the Compartment Model only the turret and hull armors, fuel tanks, gun tube, live ammunition and suspension systems are modeled in relatively complete detail.

4. Robert Shnidman, *Direct Fragment Lethality Inference from Witness Plate Array Data*, Proceedings of the ADPA Tenth Annual Symposium on Survivability and Vulnerability (SECRET-NOFORN), 10-12 May 1988, San Diego, CA.
5. Robert Shnidman, *HOLES Program Documentation*, BRL Software, July 1988. (Unpublished.)
6. Gary S. Moss, *FRED Program Documentation*, BRL Software, February 1989. (Unpublished)
7. D. L. Rigotti, P. H. Deitz, D. F. Haskell, M. W. Starks, D. P. Kirk, O. T. Johnson, J. R. Jacobson, W. Kokinakis, J. T. Klopocic and G. A. Bowers, *Vulnerability/Lethality Assessment Capabilities: Status, Needs, Remedies*, Ballistic Research Laboratory Special Publication BRL-SP-74, December 1988.
8. Robert Shnidman and Todd J. Fisher, *Abrams Tank System Component Vulnerability: Test Procedures and Results*, Ballistic Research Laboratory Memorandum Report. In Preparation.
9. M. J. Muuss, P. C. Dykstra, K. A. Applin, G. S. Moss, P. R. Stay and C. M. Kennedy, *A Solid Modeling System and Ray-Tracing Benchmark Distribution Package*, Ballistic Research Laboratory CAD Package, Release 3.0, SECAD/VLD Computing Consortium, 2 October 1988.
10. Paul H. Deitz, William H. Mermagen, Jr., and Paul R. Stay, *An Integrated Environment for Army, Navy and Air Force Target Description Support*, Proceedings of the ADPA Tenth Annual Symposium on Survivability and Vulnerability, 10-12 May 1988, San Diego, CA; also Ballistic Research Laboratory Memorandum Report BRL-MR-3754, May 1989.
11. Michael J. Muuss, *Understanding the Preparation and Analysis of Solid Models*, in Techniques for Computer Graphics, ed. Rogers and Earnshaw, Springer-Verlag, 1987.
12. Paul H. Deitz, Michael J. Muuss and Edwin O. Davisson, *Issues in Automatic Object Recognition: Linking Geometry/Material Data to Predictive Signature Codes*, In the First Proceedings of the Society of Photooptical Instrumentation Engineers (SPIE) Advanced Institute Program on Automatic Object Recognition, 21-23 April 1990, Coco Beach, FL; also Ballistic Research Laboratory Memorandum Report. In Press.

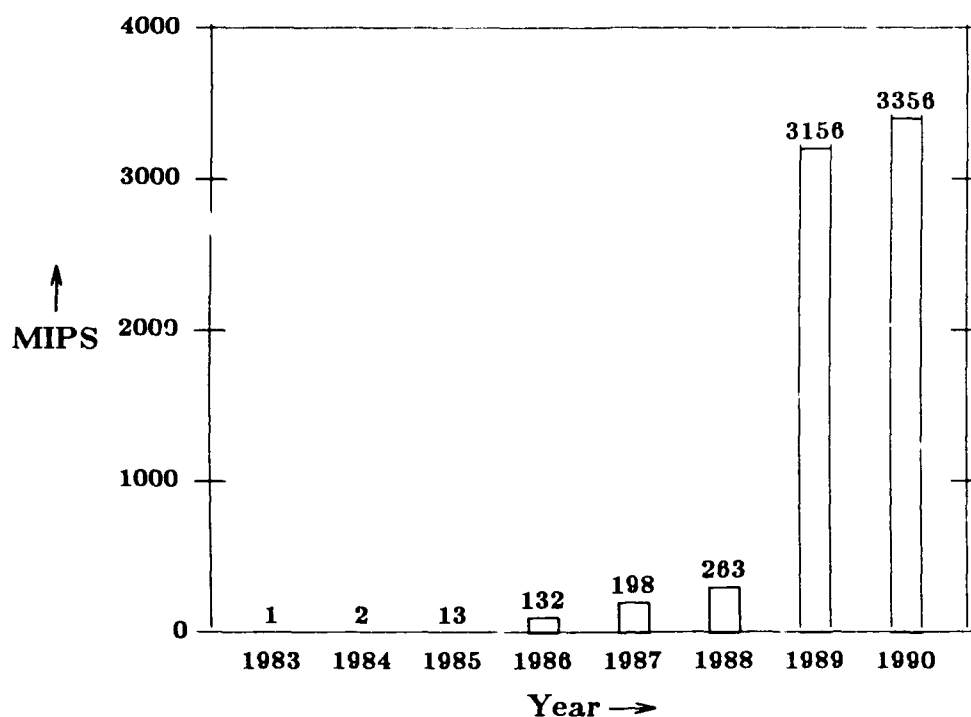


Figure 1. Plot of VLD Computing Capability *versus* Year for the past eight years. A single unit of performance is based on benchmarks established with the BFL-CAD package ray interrogation library and is equivalent to approximately one million instructions per second (MIPS), about the speed of a DEC VAX 11/780.¹³

- **Extensive Computer Hardware:** Modern computer codes require large amounts of computer power to 1] generate the copious volumes of input data, supported by interactive graphics, 2] process many millions of computations during batch-code execution, and 3] assist in the sorting, displaying and interpreting the code results, increasingly with advanced statistical packages. Figure 1 shows the growth in computing power in the Vulnerability Lethality Division (VLD) for the past eight years.
- **Uniform UNIX[®] Operating System Environment:** The ability to compile and execute monolithic FORTRAN code modules is no longer adequate to support modern analytic methods. The development and execution of modern software requires powerful editors, compilers, system subroutine libraries and high-resolution graphical display devices; also uniform intra- and intermachine communication methods for the rapid passing of data at various stages of processing. Essentially all VLD computing machines run UNIX.
- **Live-Fire Test Programs:** The National Defense Authorization Act for FY 1987¹³ required that all major weapon systems undergo live-fire testing (LFT) prior to entering full-scale production. This program, with the requirements for detailed preshot predictions and the opportunity for detailed post-shot examination of over-matched, fully configured AFVs, has been most significant.

13. *Live Fire Testing*, National Defense Authorization Act for FY 1987, contained in Chapter 139, Section 2366 of Title 10, United States Code.

As the program has proceeded it has highlighted much-needed extensions in experimental data bases, inadequacies of extant modeling methods and required statistical methodology. As various AFVs have been tested, not only full-scale test results have accrued, but also many critical supporting data bases dealing with penetration, BAD and component $P_{K/H}$'s have been established. Various LF programs have frequently funded critical methodology extensions when alternate resources were unavailable.

- **SQuASH (Stochastic Quantitative Assessment of System Hierarchies):** In response to the benefits and burdens of LFT, this advanced stochastic vulnerability code (to be reviewed below) was established.^{1,14} From this new and rapidly evolving computation tool, a new reference methodology is being established which can serve as a new vulnerability standard for a diverse set of V/L requirements.

This paper targets a number of objectives. We begin by reviewing the uses and applications of various types of Vulnerability/Lethality (V/L) data. We will note various aspects of V/L practice which have been the focus of both external and internal criticism. Next, a framework within which V/L modeling can be understood will be presented and illustrated with various aspects of both testing and modeling practices. Following this, the full utility of the SQuASH vulnerability model will be described with its applications to various required tasks. We will describe a strategy for validating SQuASH via tests of diverse military targets (with relevant threats) to form a reference model set capable of supporting both high-demand predictions as well as supporting a hierarchy of lower-resolution models. Finally, we will discuss future directions for V/L modeling.

2. USES OF V/L MODELS

The potential uses of V/L models are many and varied. For completeness, we review some of the principal applications:

- **Major Milestone Decisions:** All major Army systems must pass a series of milestone decision points. The studies which drive these decisions require vulnerability data, historically in terms of Catastrophic (K) Kill and Mobility (M) and Firepower (F) Loss-of-Function (LoF) estimates.
- **Concept Tradeoffs:** Within the development process there frequently is a need to downselect concepts, technologies, or contractors. V/L assessments provide key inputs for these studies.
- **Data for Decision Makers:** Apart from major decision milestones, Army leadership commissions numerous *ad hoc* studies to help with in-process reviews (IPRs), Program Objective Memorandum (POM) submissions, reprogramming actions, Congressional inquiries and resource decrement drills. V/L estimates are a critical input for these studies, second in importance only to cost.
- **Inputs to War Games:** War game outputs such as loss-exchange-ratios are an important data point throughout the Acquisition Process; they are also critical in helping TRADOC (USA Training and Doctrine Command) in its continual reformulation of warfighting doctrine, tactics and Operational and Organizational (O&O) Plans. Perhaps the most dominant variable in a typical force-level simulation or wargame is the V/L estimate.
- **Vulnerability Reduction:** Protection for AFVs from an array of modern threats is a key consideration both for fielded systems as the threat changes and grows and also for vehicles throughout the development cycle. During the concept stages, generally only the armor package,

14. A. Ozolins, *Stochastic High-Resolution Vulnerability Simulation for Live-Fire Programs*, The Proceedings of the Tenth Annual Symposium on Survivability and Vulnerability of the American Defense Preparedness Association, Naval Ocean Systems Center, San Diego, CA, 10-12 May 1988.

fuel and ammunition stowage are amenable to analyses. As system detail grows, interior component placement and vulnerability susceptibility and system redundancies become issues.

- **Lethality Optimization:** The acquisition of a system to deliver a warhead must be based on its ability to disable specific targets. Often many design tradeoffs must be weighed in order to achieve an optimum design. V/L codes provide key guidance in this objective.
- **SPARC (Sustainability Predictions for Army Component Requirements for Combat:** For many years the Army stockpiled spare parts for ground vehicles based on peacetime failure rates, despite the fact that there was little reason to suspect that such a stockpile would be optimally useful for repairing combat-damaged vehicles. With the help of component-level V/L predictions, the logistics community is now better equipped to develop appropriate stockpile needs.
- **Planning and Analysis of LF Testing:** Although earlier a point of contention,¹⁵ it is now widely acknowledged that LF testing alone cannot provide a complete vulnerability picture of a vehicle. High-resolution modeling methods are indispensable for delineating test configurations for which high- or low-predictive capability may exist.^{16,17} They are also indispensable for "bootstrapping" valuable, but contextually limited, full-up and off-line experimental data into a more complete picture of overall vehicle vulnerabilities.
- **Use of Reference V/L Models for Calibration:** As implied above and will be illustrated below, V/L models reflecting a given level of accuracy can be used to calibrate lower-resolution models which for certain applications may have advantages of speed or input preparation or for when detailed input information may not be available.
- **Generation of New Measures-of-Effectiveness (MoEs):** In many instances, the desired output of a V/L model is not a characterization of system damage *per se* but rather a related figure-of-merit or MoE. The standard metrics for AFV studies are the K-Kill and M and F LoFs mentioned above. As new systems are conceived and new strategies evolve, users of V/L data sometimes require higher resolution figures-of-merit than the traditional M and F LoFs. When new systems are developed for new battlefield roles, sometimes new MoEs must be defined. High-resolution V/L models capable of capturing detailed system design and damage characterization are critical to defining improved figures-of-merit.

3. CRITICISM OF V/L PRACTICE

The various uses of V/L data which were detailed in the previous section demonstrate the critical importance of VLD's work in the research, development and acquisition process. When the importance of the work is considered in light of the relatively unrefined simulation tools which have traditionally been used for the calculations, it is easy to understand why the V/L assessment process has been a magnet for high-level attention and criticism. Over the past thirteen years the VLD has been reviewed by more than a dozen oversight committees. It has periodically conducted its own self examinations. A sampling of these events includes:

-
15. *Live Fire Testing: Report to the Chairman, Subcommittee on Seapower and Strategic and Critical Materials, Committee on Armed Services, House of Representatives, United States General Accounting Office Report GAO/PEMD-87-17, August 1987, p. 124.*
 16. C. J. Dively, S. L. Henry, J. H. Suckling, J. H. Smith, W. E. Baker, D. W. Webb and P. H. Deitz, *Abrams Live Fire Test Program: Comparison Between SQuASH Predictions and Field Outcomes (U)*, Ballistic Research Laboratory Special Report (SECRET), February 1989.
 17. Paul H. Deitz, Jill H. Smith and John H. Suckling, *Comparisons of Field Tests with Simulations: Abrams Program Lessons Learned, Proceedings of the XXVIII Annual Meeting of the Army Operations Research Symposium, 11-12 October 1989, Ft. Lee, VA, pp. 108-128; also Ballistic Research Laboratory Memorandum Report BRL-MR-3814, March 1990.*

- 1977: The Hardison Report on the Review of the Vulnerability Program
- 1977: Plans for Updating the Armored Vehicle Lethality/Vulnerability Methodology and Data Base¹⁸
- 1978: Letter— GEN Starry to GEN Guthrie on Problems that Plague the Analytical Community
- 1978: Letter— GEN Guthrie to GEN Starry on Resource Requirements for Vulnerability and Performance Data
- 1982: Memorandum for Record on Air Defense Evaluation— Mr. Walter Hollis
- 1985: Defense Science Board Report on Armor Anti-Armor Competition
- 1986: USA Laboratory Command (LABCOM)-Sponsored Los Alamos Review on Live-Fire Testing and Methodology
- 1986: Department of the Army Inspector General Review of the Bradley Fighting Vehicle/Joint-Live Fire Programs
- 1986: Board on Army Science and Technology (BAST) Report on Shot Selection Process for Live-Fire Testing
- 1987: USAMARDA Manpower Survey of the Vulnerability/Lethality Division
- 1987: US Army Audit Agency- Materiel Survivability and Vulnerability
- 1987: Peer Review Group (R. Andreas, J. W. Tukey and M. Wilkins)
- 1987: General Accounting Office (GAO) Live-Fire Testing Report¹⁵
- 1987: Vulnerability/Lethality Assessment Capabilities- Status, Needs, Remedies¹⁹
- 1989: Board on Army Science and Technology Report on Vulnerability Assessment Methods²⁰
- 1990: Vulnerability Methodology Review, Convened by the Director, Ballistic Research Laboratory
- 1990: Letter— Mr. Abraham Golub to Mr. Walter Hollis, Review of the Board on Army Science and Technology (BAST) Review of the Army Assessment Methodology Concerning Vehicle Vulnerability to Anti-Armor Weapons
- 1990: JASON Review of the Army Approach to Vulnerability Testing

Many of the suggestions and recommendations made by these committees concern matters which are not directly relevant to the methodological issues discussed in this paper. Such matters include:

- The Army's institutional failure to implement recommendations of previous studies.
- Organizational bias/independent assessment issues.

18. D. F. Menne, G. L. Durfee, R. L. Kirby, J. P. Lambert, M. L. Lampson, J. J. Ploskonka, J. R. Rapp and E. P. Weaver, *Plans for Updating the Armored Vehicle Lethality/Vulnerability Methodology and Data Base*, Special Report for the Director, Ballistic Research Laboratory, 22 August 1977.

19. D. L. Rigotti, P. H. Deitz, D. F. Haskell, M. W. Starks, D. P. Kirk, O. T. Johnson, J. R. Jacobson, W. Kokinakis, J. T. Klopce and G. A. Bowers, *Vulnerability/Lethality Assessment Capabilities- Status, Needs, Remedies*, Ballistic Research Laboratory Special Publication BRL-SP-74, December 1988.

20. *Armored Combat Vehicle Vulnerability to Anti-armor Weapons: A Review of the Army's Assessment Methodology*, Committee on a Review of Army Vulnerability Assessment Methods, Board on Army Science and Technology, Commission on Engineering and Technical Systems, National Research Council, National Academy Press, Washington, D.C., 1989.

- Insufficient funding/staffing issues.
- Lack of appropriate input data for V/L models.

However, also of interest is the fact that deficiencies in the existing suite of V/L models were noted by many of the groups. Three prominent examples are the BAST review, the LABCOM-sponsored Los Alamos Review and the Golub Review. In the 1986 Report on Vulnerability Assessments, the BAST concluded that models in their current state leave much to be desired. In the 1986 Los Alamos Review, equally strong conclusions were drawn about V/L modeling:

- Characterize models in terms of variability of their output relative to their input.
- Modeling effort at BRL could be increased several fold and the cost would still be insignificant compared to overall cost of the program.

Finally, the 1990 Golub Review explicitly suggested that SQuASH be made the primary member of a vulnerability modeling hierarchy. The modeling strategy in this paper is intended to be responsive to these suggestions.

4. V/L FRAMEWORK

In an earlier paper¹ we introduced the notion of "Spaces" of vulnerability. That notion is reiterated here because it provides an extremely useful framework into which the many test/model configurations, processes/transformations and intermediate/final observations can be clearly and concisely cast.

Figure 2 is meant to represent four **Spaces** of vulnerability. **Space 1]** describes all possible encounters of a particular threat with a given target. Each point within the space represents a single configuration prescribing the attack of the target by a warhead. It is appropriate to think of a point within **Space 1]** as representing the complete pre-shot physical characterization of a live-fire test including the warhead, the target and the warhead attitude and hit-point with respect to the target. **Space 1]** is clearly infinite. Even if the space were restricted to a single warhead, single target and single intended aimpoint, the number of attack configurations is infinite. Further, even with the most detailed information concerning a highly calibrated test, certain information critical to the test outcome cannot be known *a priori*. Such information includes the *exact* physical specification of the warhead, the *exact* specification of the armor and vehicle components, the *exact* juxtaposition of the warhead and target at the moment of impact (as in the case of the Kinetic Energy [KE] round) or warhead initiation (as in the case of the Chemical Energy [CE] round).

Space 1], while establishing a complete set of initial (preshot) conditions describing the threat and the target, *says nothing* concerning the V/L mechanisms of damage and how they occur. This is the province of the mapping function, symbolically represented as the upper-most arrow in Fig. 2. The arrow can be thought of as an *operator* which transforms a state of **Space 1]** to a state of **Space 2]**. In an entirely equivalent sense a live-fire shot can be thought of as the real-world operator which performs the same transformation. As we'll see later, the SQuASH vulnerability code was configured in such a way as to replicate the same mapping function. Each point in **Space 2]** represents a list of vehicle components which have been killed by the event. Associated with that vector is a list of post-shot observables such as armor entry/exit holes, observed fragment effects, etc. The *subset* of **Space 2]** characterizing component-damage vectors is large, but *not* infinite, having a maximum size of 2^n , where n is the number of critical components[†] constituting a particular military system. Given the inherent

[†] A *critical component* of a military system is a component which if damaged or destroyed could *potentially* lead to a partial or total loss of a mission-supporting function. Such functions include mobility, firepower, communications and the ability to acquire enemy targets.

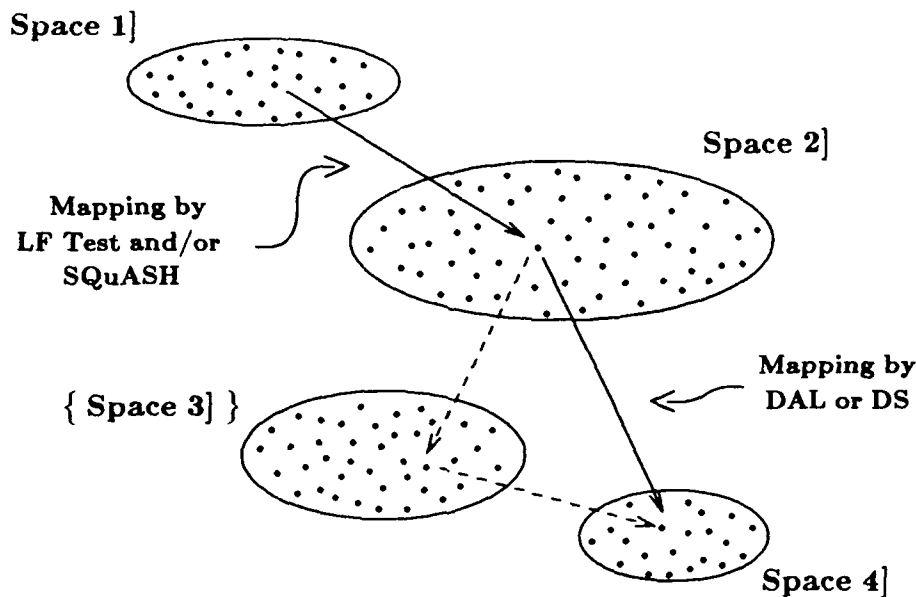


Figure 2. Four Spaces of Vulnerability. Space 1] represents all combinations of specific warhead/target initial conditions. A given point represents one complete set of specifications. Individual points in Space 2] represent particular damage vectors, i.e. particular combinations of killed critical components, plus all post-shot damage observables such as armor exit holes, fragment effects, etc. The maximum size of the subset of Space 2] describing damage vectors is 2^n , where n is the number of critical components in the target. Space 3] represents objective Measures-of-Performance and is not modeled so the related mapping processes are indicated as dashed lines. Space 4] characterizes various Measures-of-Effectiveness; the mapping process for ground vehicles has historically been via the Damage Assessment List (DAL). In the future all mapping will be via the Degraded States (DS) methodology.

variability of the many variables described above, it is likely, even to be expected, that if an experiment were repeated numerous times, many arrows would be observed, all emanating from a single point in Space 1], and mapping to many different points (damage vectors) in Space 2].[§]

Space 3] is the space of Measures-of-Performance (MoP). MoPs would typically include objective measures of automotive performance (e.g. top speed, acceleration, rough-terrain crossing ability) and firepower (e.g. rate-of-fire, time-to-acquire, hit dispersion). Given a specific damage vector (point) in Space 2], the above-mentioned MoPs could *in principle* be objectively measured in the field. The relationship between Space 2] damage states and Space 3] MoPs, though of great potential utility, has never been developed, and, hence, the associated mappings to and from Space 3] are shown as dashed lines and the Space 3] label is enclosed in curly brackets ({ }).

§ An interesting variant of this case is to consider a sequence of *different* experiments performed in Space 1]. Given many such experiments in which the warhead/target configuration were varied (i.e. sampling different points of Space 1]), cases could be observed in which the *same* damage vectors occurred. This would be described by multiple arrows originating at different points in Space 1] but terminating at the same point in Space 2].

The last space of vulnerability is **Space 4**], a space of Measures-of-Effectiveness (**MoE**). For many years these measures have been known as probabilities of catastrophic kill (probability of K Kill), and Mobility and Firepower Loss-of-Function (**M** and **F LoF**). In the past the mapping from **Space 2**] to **Space 4**] was accomplished by means of the Damage Assessment List (**DAL**). Described elsewhere,¹ this process is being replaced by an improved mapping process called Degraded States (**DS**).²¹⁻²³

The issue which lies at the heart of V/L field tests and/or simulations is the statistical characterization of these spaces. For example in the case of **Space 1**], even if this domain can be artificially limited by reducing the number of threats and interaction geometries with a specific target, the variability of warhead penetration and other phenomenologies introduced by the projection from **Space 1**] to **Space 2**] nevertheless gives **Space 2**], the physical domain within which all observations take place, a high level of complexity. Stated slightly differently, for a particular warhead/target interaction in **Space 1**], what is the dimensionality of **Space 2**], i.e. how many individual damage vectors compose the space of the 95th percentile? Such issues were the focus of Ref. 17, and statistical tests were used where possible for all physical observables. As we have also observed, if a model can accurately predict the statistical behavior of a V/L test with respect to the physical observables of **Space 2**], then the (mapped) metrics of derived spaces (e.g. **Space 4**]) must agree.²⁴ Thus issues of accuracy and precision in the context of V/L considerations can only be calculated in **Space 2**], since model accuracy by definition implies some statistical convergence with the real world and by our paradigm, the post-shot real world is embodied *only* in **Space 2**] metrics.

Finally using these spaces, all V/L models can be described within this framework. The Compartment Model was based on a series of firings² in which each shot (defined by a point in **Space 1**]) resulted in a set of killed components (damage vector) and armor exit hole (both of **Space 2**]). For each test the damage vector was mapped from **Space 2**] to **Space 4**] in a partly subjective process by the following procedure. The DAL was established to relate the total loss[∞] of any single major component/system directly to overall vehicle M and F LoF values. Utilizing the DAL for post-shot assessments required taking into account two complications— fractional (partial) system kills and/or multiple-system kills. To handle partial kills, the DAL entries were scaled by fractional kill values based on assessor judgements. To handle multiple-system kills, the scaled system LoFs were combined using a Survivor Rule type of relationship.[§] The total vehicle LoFs (i.e. the M and F metrics) were then decomposed into the contributions attributable to particular vehicle regions (i.e. compartments). The resulting points were used to generate curves expressing the relationship between armor exit hole[□] and the M and F LoFs for the crew and engine compartments.[‡] During actual execution of the

21. Michael W. Starks, Lisa K. Roach and John M. Abell, *Degraded States Vulnerability Analysis*, Ballistic Research Laboratory Technical Report BRL-TR-3010, June 1989.

22. John M. Abell, Bruce A. Rickter and Mark D. Burdeshaw, *Degraded States Vulnerability Methodology - Phase II*, Proceedings of the XXIX Annual Meeting of the Army Operations Research Symposium, 10-11 October 1990, Ft. Lee, VA.

23. Gary R. Comstock, *Degraded States Weapon Analysis Research Simulation (DSWARS)*, Proceedings of the XXIX Annual Meeting of the Army Operations Research Symposium, 10-11 October 1990, Ft. Lee, VA.

24. Michael W. Starks, *Assessing the Accuracy of Vulnerability Models by Comparison with Vulnerability Experiments*, Ballistic Research Laboratory Technical Report BRL-TR-3018, July 1989.

∞ A system Loss-of-Function is not Bernoulli in nature but can take values $0.0 \leq \text{LoF} \leq 1.0$.

§ The "LoF" Survivor Rule states that the overall LoF of an AFV consisting of n independent systems, each with its own Damage Assessment Value, D_i , and system Fractional Kill, F_i , is given by:

$$\text{LoF} = 1 - \left[(1 - D_1 F_1) \times (1 - D_2 F_2) \times \dots \times (1 - D_n F_n) \right]$$

□ For shaped-charge threats, the hole diameter was used for the crew compartment and was combined with the residual penetration (i.e. residual hole volume) for the engine compartment.

‡ Since the application of the Compartment Model to the M1 vehicle, an ammunition compartment has been added.

Compartment Model, the various Compartment LoFs are aggregated using a variant of the Survivor Rule[†] given earlier. Thus the Compartment Model uses an extremely incomplete characterization of **Space 2**], armor exit hole (or residual penetration), to provide mapping relationships to the expected M or F LoFs of **Space 4**].

Figure 3 gives one of the damage-correlation curves for the Crew Compartment based on the early CARDE tests.² Here the Mobility (M) LoF is plotted against the Profile Hole Diameter, a parameter related to the hole diameter on the inner surface of the armor. These data were collected for a series of Chemical Energy warheads ranging in size from 5" to 8"; firings were conducted against both M47 and M48 tanks.

The class of vulnerability models called point-burst codes describe explicitly the behind-armor debris environment and its interaction with the vehicle interior components; it can be understood as the following mapping processes. Codes such as VAST²⁵ and SLAVE²⁶ estimate the probability of killing each vehicle interior component for a given shot. In contrast to the manner in which the CARDE data were processed, all of the vehicle major systems are decomposed into their constituent components. The components are cast into fault trees which reflect the series/parallel design of the systems. Then the individual component kills are rolled up using the standard laws of probability for independent series or parallel constructs as reflected in the fault trees. The resulting system LoFs are finally combined using the procedure described above for the CARDE Compartment-Code calibrations. Two related issues are that 1) the probability procedures applied to the (critical) component PKs and 2) the Survivor-Rule procedure applied to system LoF aggregation are strictly applicable only under the assumption that the elements being processed (components and/or systems) are *independent*, one from another. Based on analyses of tests reported in Ref. 17, we know that component kills are, in fact, statistically *dependent*. The net result is a *biased** estimate of the overall system first-moment values for the M and F LoFs. Expected-value point-burst models have not been typically configured to infer actual **Space 2**] damage vectors but have resorted to the above-described processes to proceed directly to expected-value LoFs.

Finally, SQuASH is a point-burst model into which stochastic processes have been introduced. Through repeated Monte Carlo draws, an attempt is made to demonstrate the possible variability of single live-fire shots. The effect is to repeat the mapping projection from **Space 1**] to **Space 2**] to derive individual outcomes of damage vectors. Bernoulli outcomes (either kill or no-kill) are assigned to all classes of components.[‡] Thus using SQuASH, we have attempted for the first time to model the full characterization of damage vectors in **Space 2**]. The key metrics of **Space 2**] can then be used to compare with field tests[§] as well as to map unambiguously to **Space 4**] for the required MoEs. In SQuASH the fault-trees are assembled in identical fashion as required in the expected-value point-burst codes. However, since all components are either killed or not-killed, system functions are either fully supported (i.e. there is at least one unbroken path through the fault tree) or completely unsupported

† The version of the *Survivor Rule* used in the Compartment-Model calculations states that the overall LoF of an AFV consisting of *n* independent compartments/major systems, each with its own LoF_{*i*}, is given by:

$$\text{LoF} = 1 - \left[(1 - \text{LoF}_1) \times (1 - \text{LoF}_2) \times \dots \times (1 - \text{LoF}_n) \right]$$

25. C. L. Nail, *Vulnerability Analysis for Surface Targets (VAST)- An Internal Point-Burst Vulnerability Assessment Model - Revision 1*, Computer Sciences Corporation Technical Manual CSC TR-82-5740, August 1982.

26. D. A. Ringers and F. T. Brown, *SLAVE (Simple Lethality and Vulnerability Estimator) Analyst's Guide*, Ballistic Research Laboratory Technical Report ARBRL-TR-02333, June 1981, AD B059679.

* The amount of this bias is unknown at this time.

‡ The rationale for this binning process is discussed in Ref. 17.

§ An issue here is the reliability and consistency with which field assessors can bin *partially* killed (i.e. damaged) components to crisp kill/no-kill states.

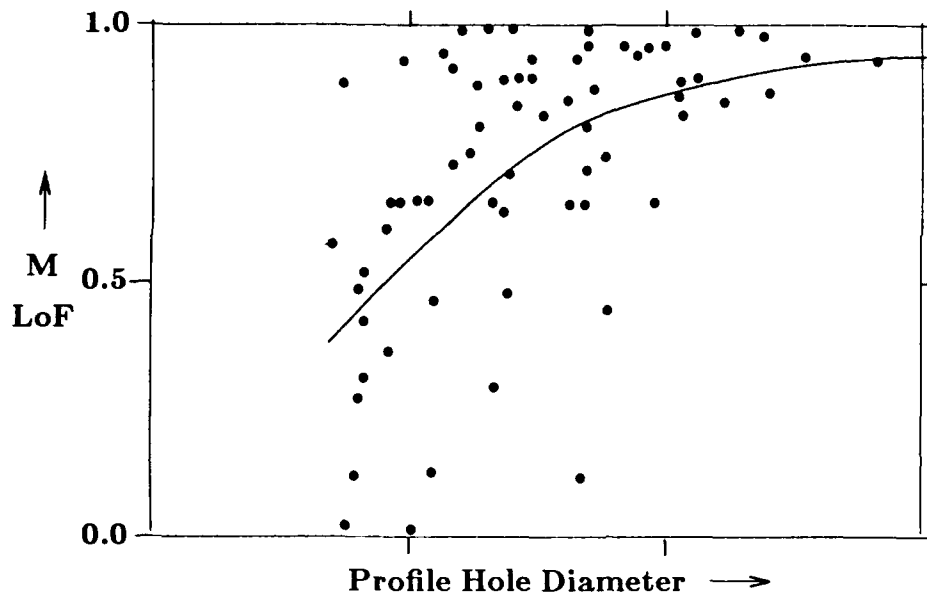


Figure 3. Mobility LoF vs. Profile (\approx Exit) Hole Diameter. Data (circa 1959) from CARDE Tests² for a series of Chemical Energy (CE) warheads ranging from 5" - 8".

(i.e. there is no unbroken path through the fault tree). At the major component/system-level entry points to the DAL process, multiple system kills are unavoidably combined *via* the Survivor Rule when two or more kills occur. As we will see later, the Degraded States methodology avoids altogether the need for using the Survivor Rule.

The importance of **Space 2]** characterization as the *only* domain within which issues of model accuracy^{24,27} can be grounded went unappreciated by the BAST²⁰ during their 1989 assessment. The first VLD attempt at comparisons¹⁷ merely showed some of the possibilities for statistical analyses. Recent work at Institute for Defense Analyses²⁸ has provided three new statistical tests for comparing field and predicted damage vectors. Ongoing work by the JASONS²⁹ is also targeted to developing statistical methods for LF-test/SQuASH-model comparisons in **Space 2]**.

We will now review the *reference* model being developed to act as the *standard* for V/L methodology.

5. SQuASH AS KEY MEMBER

For SQuASH to serve as the reference model for Vulnerability/Lethality methodology, it must embody the highest level technical understanding of threat/target interaction available. Furthermore, this technical understanding must be anchored in experiment through validation with full-scale field tests.

27. Michael W. Starks, *Vulnerability Science: A Response to a Criticism of the Ballistic Research Laboratory's Vulnerability Modeling Strategy*, Ballistic Research Laboratory Technical Report BRL-TR-3113, June 1990.

28. L. Tonnessen, A. Fries, L. Starkey and A. Stein, *Live Fire Testing in the Evaluation of the Vulnerability of Armored Vehicles and Other Exposed Land-Based Systems (U)*, Institute for Defense Analyses Paper P-2205 (SECRET), July 1989.

29. Private communication with Oscar Rothaus, member, JASON Committee to Investigate Vulnerability Testing, La Jolla, CA, July 1990.

In the previous section, some of the technical differences among the various V/L codes were detailed. In this section we will enumerate the technology advances of SQuASH beyond previous models, detail the plan for validating the model, and give some recent extensions of SQuASH that, when taken together, will establish SQuASH as the reference model.

5.1 Technical Improvements Provided by SQuASH

5.1.1 Stochasticism: The most significant improvement to SQuASH over previous models is the inclusion of random sampling for the variables that contribute to the vehicle LoF. All previous models computed only an expected-value estimate of the vehicle LoF, with no associated variability of the estimate. With the need to compare the predicted outcome of a given shot from live-fire tests with an actual observed outcome, the addition of the random nature of the phenomena is critical in making statistically valid and meaningful comparisons. Furthermore, there are no statistically valid decision criteria based only on expected-value point estimates of random variables.

5.1.2 Physics for Kinetic Energy (KE) Penetrators: SQuASH makes two improvements over earlier models to represent more accurately the threat/target interaction under some specific conditions. First, SQuASH allows KE penetrators to deflect through the target geometry rather than traveling only along a straight path and, second, it allows KE penetrators to fracture, with the separate pieces tracked through the target where this phenomenon is expected.

5.1.3 Truncation of Intermediate Results: Many of the older V/L models truncate calculation along a shotline when the accrued damage to the vehicle reaches unity. This is done to reduce the computation time and storage required to run the code. In contrast, SQuASH saves all intermediate output. If a penetrator perforates the armor and travels through five components, even though the first component may cause complete loss-of-function, all other components and the intermediate damage are stored. This is important for the development of lower-level models where the distribution of hits on given components or other information may be of interest. If this information is truncated, it can also give biased estimates of the vulnerability of individual components.

5.1.4 Improved Realism: An additional advantage of the SQuASH model is the similarity between the structure of the code and the actual physical processes as they occur in the real world. This structure facilitates comparisons between the model and the field data that can be observed at any stage in the process. In particular there is no combining of effects; each is modeled explicitly.

Before SQuASH, as discussed above, no V/L codes provided estimates of actual component-damage vectors for repeated sampling of warhead/target interaction. Also as noted, since these **Space 2** metrics are the modeling-world equivalent of test observables, without them model calibration is problematic at best, and validation is impossible.

5.2 Recent SQuASH Extensions

Since the original Abrams program LF requirements, the SQuASH environment has been extended to support other classes of V/L computations. They will be reviewed briefly now.

5.2.1 Batch Computation: The original configuration of SQuASH, as previously noted, was targeted to single-shot predictions. Once all the inputs were assembled, the computation proceeded in two stages. The first involved extensive geometric interrogation *via* raycasting to replicate possible warhead/target paths as well as vehicle interior components behind the armor potentially susceptible to residual penetrator and BAD damage. This part of the processing required a substantial amount of processing (~ 30 minutes of CRAY 2 time for a single shot location).

The second involved the actual vulnerability computations leading to the **Space 2** damage vectors and LoF histograms. This calculation took substantially less time. Nevertheless, the application of SQuASH to many thousands of hit points from, for example, a single aspect angle was not practical.

Considerable effort was expended to reduce the run-time. A data-compaction scheme was developed to reduce the total number of ray calculations required for the interior component solid angle

calculations. The result is a run overhead for SQuASH that is consistent with previous point-burst models such as VAST²⁵ and SLAVE.²⁶

5.2.2 Support for Degraded States: The initial use for the batch-mode calculational procedure just described was in support of the improved V/L methodology called **Degraded States (DS)**. Traditional vulnerability calculations make use of a mapping procedure called **Damage Assessment Lists (DALs)** or **Standard Damage Assessment Lists (SDALs)**. A DAL maps killed components (**Space 2**) and sets of components into loss of combat function (LoF) in **Space 4**. However, the use of DALs in the process of developing vulnerability measures-of-effectiveness is conceptually and mathematically problematic.³⁰ The Degraded States Vulnerability Methodology,²¹ developed by the BRL and the Army Materiel Systems Analysis Activity (AMSAA) is a material improvement in both the fundamental method by which vulnerability estimates are calculated and in the clarity, objectivity and usefulness of the estimates themselves. The DS methodology overcomes the problems associated with the DAL. It is fully auditable and, therefore, subject to correction and improvement. It is also completely sound from a mathematical point of view. Most important, it provides a much more robust account of vehicle capability as a function of specific damage sustained. This robustness substantially improves the Army's capability to model accurately the effects of damaged, but operational, vehicles on the battlefield.

The tradition has long been to describe vehicle Loss-of-Function in terms of mobility and firepower. For the new approach, a more robust set of metrics was developed. The functions of a tank were divided into six categories: **MOBILITY, FIREPOWER, ACQUISITION, CREW, AMMUNITION and COMMUNICATION**. Each category contains a set of kill definitions which describe degraded, but operational, states of the tank. Particular tank subsystems which support each category/kill definition were identified and committed to fault-tree analyses.³¹ Damage was then assessed against the various vehicle subsystems used to represent the category/kill definitions for a particular set of threats. The probabilities of the various combinations of kill definitions for each subsystem were calculated based on the SQuASH estimates within each four-inch cell from a particular direction of attack. These estimates were calculated for both the Degraded States vulnerability approach and the DAL approach. The probability distributions were provided to AMSAA for support in demonstrating the new metrics in force-level modeling and have been supplied to many other downstream consumers of V/L products. BRL is in the process of fully implementing this improved approach to **Space 4** MoEs.

5.2.3 Support for SPARC Calculations: A second important use of the batch-mode version of SQuASH has been to determine appropriate spare-parts stockages for combat-damaged materiel. Although not part of the original code design,¹⁴ the batch-mode capability together with significant algorithm extensions[†] have provided for SPARC capability with direct-fire weapons. Here it is not the **Space 4** MoEs that are of interest, but the **Space 2** damage vectors. Clearly, this class of calculation would not be possible at all without credible component-level modeling at the SQuASH level of detail.

This methodology is currently being extended to indirect-fire (i.e. artillery) weapons as well.[‡] For many years the standard vulnerability metric computed for such encounters has been (expected) *vulnerable area*. However vulnerable area, like the M and F LoFs, cannot be compared with specific

30. Michael W. Starks, *New Foundations for Tank Vulnerability Analysis, The Proceedings of the Tenth Annual Symposium on Survivability and Vulnerability of the American Defense Preparedness Association*, Naval Ocean Systems Center, San Diego, CA, 10-12 May 1988.

31. The interactive computer program which supports this function is called ICE (for Interactive Criticality Estimator), written by G. S. Moss. Documentation appears in the VLD/VMB UNIX Supplementary Manual, D. A. Gwyn, Editor, Ballistic Research Laboratory, 29 August 1987.

† The analysis and coding for these extensions are due to Robert N. Schumacher and Aivars Ozolins, IRL/VLD

field observables. At a minimum, the stochastic extensions under development will produce field-observable outputs.

5.2.4 Derivation of Lower-Level Models: If SQuASH is to be the key member of a V/L modeling hierarchy, then a sound strategy for referencing low-resolution models to it must be developed. The most direct way to develop low-level models that are calibrated to SQuASH is by direct derivation. One method of doing this, suggested earlier,¹⁸ involves deriving new Compartment correlation curves from high-resolution model outputs and then using those curves as inputs to the lumped-parameter Compartment Model discussed above. In this way, the results from the low-resolution Compartment Model would be hierarchically grounded in SQuASH.

The feasibility of generating new correlation curves using SQuASH has been successfully demonstrated as shown in Fig. 4. Here the SQuASH code has been used to fire approximately 1500 shots into the side of a tank. The subset perforating into the crew compartment was used to form the left-hand plot of Fig. 4. For each M/F (read M or F) LoF, a corresponding Profile Hole Diameter was computed and used as the independent variable. This plot corresponds in *form* to the field-derived results shown above in Fig. 3. The M/F LoFs shown on the left were averaged by narrow bins and fitted to an exponential curve; these results are plotted on the right of Fig. 4. The aspect-averaged Compartment curve for Firepower in recent use is also shown.

If we accept this approach, we can then consider other variables that SQuASH calculates as possible independent variables with which to correlate the M/F LoF as shown in Fig. 5. Here the data derived for Fig. 4 are plotted as function of the number of critical components killed.[∞] On the right, the M/F LoF are averaged by the number of (critical) components killed and fitted to an exponential curve.

Nevertheless, the general approach of using but a single variable as a basis for describing **Space 4** metrics is unlikely to provide a sound statistical basis for a functional representation. It is not to be expected that such complex behavior can be described by a limited set of variables. This issue will be further discussed in **Section 6**.

5.3 Validation of the SQuASH Model

In addition to verifying that the SQuASH model performs as expected, the validity of the model itself must be checked with field data. Model validation here is meant in the statistical sense of *not* rejecting the null hypothesis that the model predicts accurately over the input space on which the comparisons are made. For the model to be validated in a general sense, the entire space over which predictions are to be made must be sampled. For armored fighting vehicles, a matrix of heavy and light, foreign and domestic vehicles has been selected to validate the SQuASH model using live-fire data. For the validation process, only 90% of the data collected should be used. The remaining 10% should be held in reserve for model validation in the event that null hypothesis is rejected. If the null hypothesis is rejected and the conclusion is that SQuASH does not predict vehicle component-damage vectors adequately (at some statistical level of significance), then these data can be used to modify the SQuASH model and the remaining 10% of the data that were held in reserve should be used to validate the model after changes are made. It should be clear that it is not acceptable to use the same data to develop/change a model *and* to validate it as well. A program to develop these procedures is currently ongoing and will require a substantial expenditure of resources in order to complete over the next few years.

Once the SQuASH model has been validated over the space of vehicles, it will be the only vulnerability model validated with full-scale, live-fire tests and indisputably the key member model for application to armored fighting vehicles. Other vulnerability models do not produce metrics that are

[∞] The abscissa values of the points have been dithered to make the full set of points more visible.

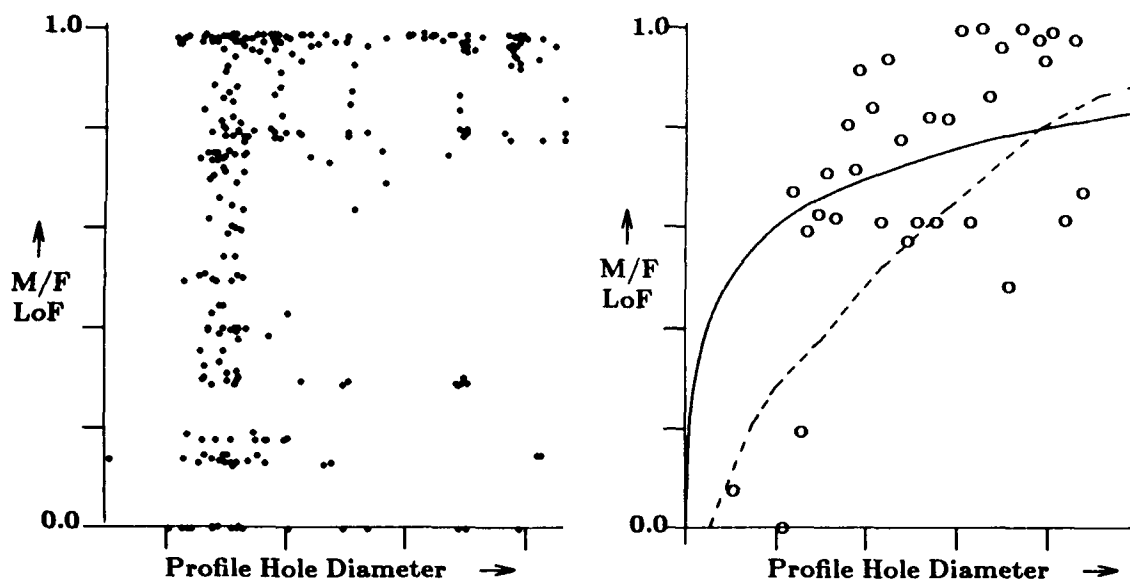


Figure 4. Predicted M/F LoFs vs. Profile (\approx Exit) Hole Diameter. On left, all shots which impacted crew compartment. On right, (o)- M/F values averaged by narrow bins; (—)- exponential curve fit to averaged values given by (o); (---)- aspect-independent damage correlation curve for Firepower.

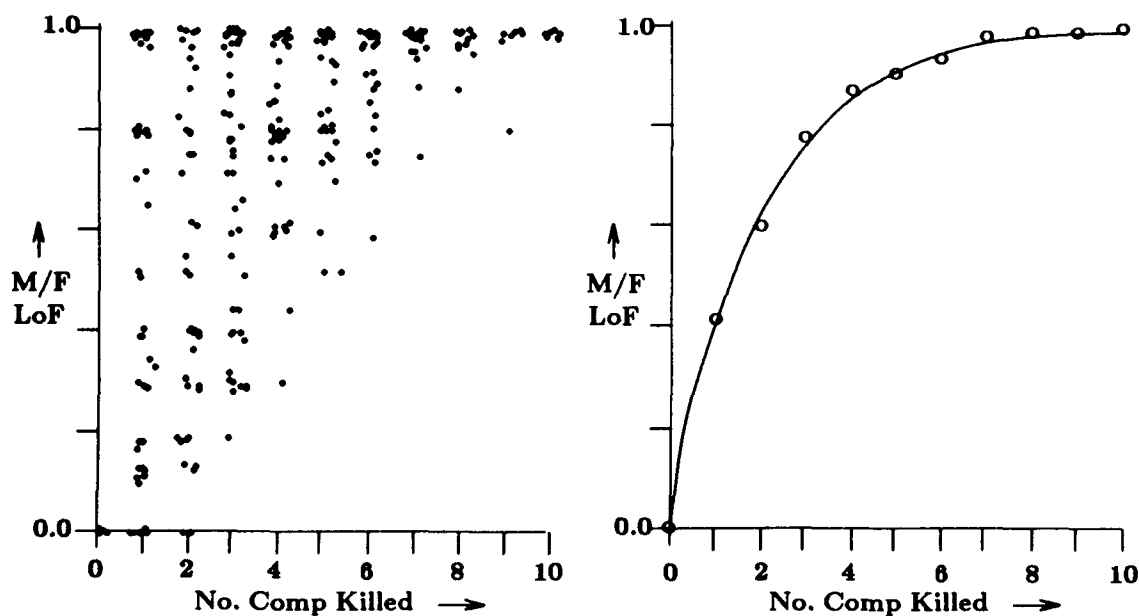


Figure 5. Predicted M/F LoFs vs. Number of Critical Components Killed. On left, raw data for those shots which impacted crew compartment. On right, (o) give expected M/F LoFs vs. number of critical components killed; solid line (—) gives exponential curve fit.

appropriate for comparison with individual samples produced by live-fire test programs. Furthermore, SQuASH is being validated at every level at which data can be collected or measured in live-fire testing.

6. FUTURE DIRECTIONS IN V/L MODELING

The development of the high-resolution stochastic point-burst model and the validation of that model raise possibilities for the development of a low-resolution model. One of the requirements that makes a low-resolution model necessary is the need to conduct vulnerability analyses of concept vehicles. For such applications, detailed inputs are not available (by definition) for performing a SQuASH-level of high-resolution analysis. A desirable property of such a model is that it be subject to rapid configuration and execution.

An alternative is to find a way of making quick turn-around V/L estimates which is simultaneously calibrated with high resolution modeling but avoids the difficulties that we have seen are associated with deriving new Compartment correlation curves. One possibility involves abandoning the notion of "calibration" altogether and simply using the high-resolution model for all required V/L estimates. There are several objections to this. One objection concerns the high level of resources required for SQuASH modeling, in particular, the long lead time required for conduct of this kind of analysis. We believe that while this objection can be overcome in principle, it cannot currently be overcome in practice. Although many computer aided tools have been developed to assist with geometry editing⁹ and fault-tree construction,³¹ there is still considerable overhead in reconfiguring the input files for any high-resolution (e.g. point-burst) V/L simulation. □ A second objection to the strategy of using high-resolution modeling for some V/L purposes is that we do not often have sufficient detailed information available concerning component sizes, locations and $P_{K/H}$'s. This is obviously true for many foreign vehicles to which the US does not have access. However, it is not clear that the objection is a strong one. If sufficiently detailed information is not available about all vehicle components, then a reasonable assumption is probably that the future will be like the past. If a previous generation tank had a radio of a certain size and location, then assume (in the absence of information to the contrary) that future tanks will also have that radio in the same location. We note that some version of this assumption is made -- implicitly -- when a Compartment correlation curve for a "specified" vehicle is applied against a "loosely specified" vehicle.

The current Compartment Model qualifies as a low-resolution model. However, it is not currently referenced to a high-resolution model nor is it a particularly responsive analytical tool. Of these two shortcomings, the former can probably be rectified but not necessarily the latter. The more important issue is the statistical validity of the general approach. Thus a new low-level vulnerability model is being sought.

One promising solution to this problem involves the generation of a regression equation derived from SQuASH to form the low-resolution model. Since SQuASH is configured to retain initial, intermediate and final computations together with all supporting data files, it provides a wealth of variables for use in regression analyses that would presumably contribute to various vehicle **Space 4** metrics. One of the difficulties of this approach will be to assure that the assumptions for regression analyses are met and that no statistically pathological problems (e.g. collinearity, outliers) effect our model. Another problem with this approach is that the parameters that determine the **Space 4** metrics for the high-resolution model must be rolled-up to the level of parameters available for concept vehicles while *retaining sufficient accuracy to be useful*.

□ The Abrams M1A2 target description consists of 5000 objects, 750 of which represent critical components. Each of these components appears at least once among some 76 fault trees. Reconfiguring the target can involve the modification (resizing, reorientation, deletion) of any of the 5000 objects or the addition of new entities. If any change involves critical components, the related fault trees and component $P_{K/H}$'s must be reworked as well.

Another low-level modeling approach that could be considered is an engineering or analytical model that incorporates the effects of the target rather than the current approach in which geometry is explicitly built and raytraced. It has been shown in the first phase of the sensitivity analysis that is currently being conducted on the Compartment Model that this approach is feasible for at least some Compartment Model vulnerability measures and for certain classes of threats.³² Again this approach has potential pitfalls. If an analytical model were developed using information available at the initial concept stage (i.e. information available in the current Compartment Model), it must still be calibrated using SQuASH. Neither of these approaches is sufficiently developed to speculate on the probability of success. In each instance only preliminary computations have been made to demonstrate the approach as having possible merit.

We have asserted above that a set of regression equations with associated statistical uncertainties will be used in the future to make rapid-response V/L estimates. A final remark is appropriate to elucidate the likely extent to which such regressions will prove statistically useful in evaluating modified or new targets. The multidimensional response surface implicit in our regression will be statistically valid for a new application only if the values of the regression variables characterizing the weapon and target are within the envelope of SQuASH initial conditions that were used to develop the regression equations in the first place. Since many of the engineering changes made to weapon systems are of the incremental or product-improvement type, it is reasonable to suppose that the regression strategy will be adequate for most analytical purposes. However, we must explicitly caution that, for radically new concepts or technologies, there can be no V/L simulation method that is simultaneously quick turnaround and statistically defensible. For break-throughs, which are outside the envelope of our regression space, we see no defensible simulation alternative that does not require resort to high-resolution analysis.

7. VLD MASTER PLAN

Based on the evidence summarized above, we assert the following:

- **PRINCIPLE I:** The assessment of *accuracy* and *precision* in V/L modeling is founded upon the application of appropriate statistical assessment tools to predictions of target damage vectors. Such vectors are the observable of LF testing; they are also the unique yield of the stochastic V/L model SQuASH. Therefore **Space 2]** comparisons between (field) observed and (computer) predicted damage vectors can reveal the limitations of extant predictive tools and their ability to characterize accurately the effect of all relevant damage mechanisms.
- **PRINCIPLE II:** If reliable damage vectors can be estimated, new Measures-of-Effectiveness can be formulated in order to meet the evolving needs of relating vulnerability damage to application-specific utility. Therefore new and useful extensions to **Space 4]** can be implemented to extend the utility of the key damage vectors of **Space 2]**.
- **PRINCIPLE III:** Where needs arise for models of lower resolution than the reference model, those models should be derived directly from the high-resolution (stochastic) estimates. Bounding confidence intervals, intrinsic elements of the reference model, will carry over to lumped-parameter derivations. Very likely the current Compartment Model approach, in which damage correlation curves (e.g. Fig. 4) are based on a single parameter (e.g. profile hole diameter), will give way to models based on full exercise of multiple inputs and examined through modern statistical methods such as the Analysis of Variances.³³

32. William E. Baker, Joseph C. Collins, Elizabeth A. Laurie, Jill H. Smith and Wendy A. Winner, *Sensitivity Analysis of the Compartment Model to Cell Size and Symmetry for the Abrams Vehicle*, Ballistic Research Laboratory Memorandum Report, In Preparation

33. Charles R. Hicks, *Fundamental Concepts in the Design of Experiments*, Third Edition, Saunders College Publishing, Fort Worth, TX, 1982.

- **PRINCIPLE IV:** The **PRINCIPLES I-III** are *generic* in nature. That is they apply without regard to the *specific class* of threat/target interactions. As such, all targets, aircraft, communication shelters, as well as mobile ground systems are amenable to this strategy of analysis.

Therefore based on these **PRINCIPLES** and the arguments upon which they are based, we propose the following plan of action. Choose a set of targets that at least minimally covers those systems that are important to the Army mission, are fundamentally different one from another, and will have been subjected to live-fire testing. Proceed with each using the following steps:

1. Fully configure SQuASH for a given target. This includes full development of high-resolution geometry, component $P_{K/H}$'s, and the inclusion of all phenomenologies likely to play a role in producing target damage for the threats under evaluation.
2. Perform live-fire tests on the target.
3. Perform SQuASH calculations for each LF shot.
4. Use 90% of the data collected to validate the model using various statistical methodologies. If the null hypothesis that the model predicts vehicle LoF accurately is not rejected, then proceed to Step 8.
5. Upgrade the model to account for discrepancies observed between the live-fire data and the model using the same data (90% portion).
6. Validate the model using the 10% of the data held in reserve; if not rejected, proceed to Step 8. If the hypothesis is again rejected, go to Step 5 to examine whether further upgrades can be made.
7. Collect additional data to validate the model.
8. Derive lumped-parameter model relations through suitable statistical analyses (*e.g.* regression) in order to relate **Space 1**] initial conditions to **Space 4**] metrics.

Thus far, VLD has partially completed an analysis of this type for only one target. Consistent with the four **PRINCIPLES** articulated above, VLD has near-term plans for high-resolution stochastic analysis of several additional targets and classes of targets. Highest priority targets for this work are domestic and foreign tanks, infantry fighting vehicles, self-propelled howitzers and helicopters. The first to be examined will be two heavy tanks and at least one system from each of the other classes. For most of the targets analyzed, this will permit us to make **Space 2**] comparisons between computed damage vectors and empirically derived vectors from actual shots. These comparisons will also permit us to evaluate the evolving statistical tools for evaluating the accuracy of our predictions. This analysis will also require us to develop **Space 4**] Degraded State (DS) kill definitions for the new targets and classes of targets. Use of the DS kill definitions for calculation of **Space 4**] MoEs will provide further proof of the robustness and utility of the DS methodology. Moreover, the set of SQuASH **Space 2**] outputs and derivative **Space 4**] DS metrics will provide, for the first time, an adequate set of raw data to execute the lower-level model calibration described above in **Section 5.2.4**. At this point we will have sufficient information in hand to address questions coherently concerning economical variable sets for analysis and whether one or many sets of regression variables are required.

Last, and probably most important, the critical path to these objectives *requires* the successful prediction of critical-component damage vectors (of **Space 2**]) for all threat/target pairings. To be successful in this endeavor, all significant damage phenomenologies (*e.g.* spall, blast, shock) will have to be confronted, supporting data bases generated and LF test results thoroughly examined in order to establish a credible predictive capability. If even partial success towards this goal is achieved over the next few years, the sunk investment in LF testing will be enhanced many fold.

8. SUMMARY AND CONCLUSIONS

In this paper we've reviewed a series of developments and plans in the area of Vulnerability/Lethality simulation. To summarize:

- There are many important and diverse applications of V/L data, each with specific requirements for form, accuracy, cost and timeliness.
- Over the past fifteen years a body of criticism of V/L assessment practice has developed, some of which is technically justified.
- An analytical framework has been established within which the many vulnerability states and transformations can be understood with respect to both field testing and high-resolution simulations. Further, a high-resolution stochastic tool, SQuASH, has been developed that replicates in simulation the same sequence of processes that occur in actual live-fire tests.
- The V/L modeling paradigm described here can be generalized to *all* classes of military targets by tailoring the damage algorithms to the relevant threat phenomena.
- We suggest that a critical set of military targets, a group of those already undergoing live-fire testing, be subjected to stochastic analysis. By comparing the field observable damage with model predictions *within the context of our newly emerging statistical perspectives*, confidence bounds can be established not only for those field-observable metrics, but all other related V/L measures.
- If appropriate levels-of-confidence can be established for predictive component-damage vectors *via* the reference models *by target class*, then all other V/L metrics can be supported. These include extended Measures-of-Effectiveness, spare-parts calculations and lumped-parameter regression modeling.

ACKNOWLEDGMENT

The authors wish to thank Mr. John H. Suckling for his critical reading of this paper and Messrs. Robert L. Kirby and Gerard A. Zeller for their helpful insights into various assessment methods and modeling procedures.



No of Copies	Organization	No of Copies	Organization
2	Administrator Defense Technical Info Center ATTN: DTIC-DDA Cameron Station Alexandria, VA 22304-6145	1	Director US Army Aviation Research and Technology Activity ATTN: SAVRT-R (Library) M/S 219-3 Ames Research Center Moffett Field, CA 94035-1000
1	HQDA (SARD-TR) WASH DC 20310-0001	1	Commander US Army Missile Command ATTN: AMSMI-RD-CS-R (DOC) Redstone Arsenal, AL 35898-5010
1	Commander US Army Materiel Command ATTN: AMCDRA-ST 5001 Eisenhower Avenue Alexandria, VA 22333-0001	1	Commander US Army Tank-Automotive Command ATTN: AMSTA-TSL (Technical Library) Warren, MI 48397-5000
1	Commander US Army Laboratory Command ATTN: AMSLC-DL Adelphi, MD 20783-1145	1	Director US Army TRADOC Analysis Command ATTN: ATRC-WSR White Sands Missile Range, NM 88002-5502
2	Commander US Army, ARDEC ATTN: SMCAR-IMI-I Picatinny Arsenal, NJ 07806-5000	(Class. only) 1	Commandant US Army Infantry School ATTN: ATSH-CD (Security Mgr.) Fort Benning, GA 31905-5660
2	Commander US Army, ARDEC ATTN: SMCAR-TDC Picatinny Arsenal, NJ 07806-5000	(Unclass. only) 1	Commandant US Army Infantry School ATTN: ATSH-CD-CSO-OR Fort Benning, GA 31905-5660
1	Director Benet Weapons Laboratory US Army, ARDEC ATTN: SMCAR-CCB-TL Watervliet, NY 12189-4050	1	Air Force Armament Laboratory ATTN: AFATL/DLODL Eglin AFB, FL 32542-5000 <u>Aberdeen Proving Ground</u>
1	Commander US Army Armament, Munitions and Chemical Command ATTN: SMCAR-ESP-L Rock Island, IL 61299-5000	2	Dir, USAMSAA ATTN: AMXSY-D AMXSY-MP, H. Cohen
1	Commander US Army Aviation Systems Command ATTN: AMSAV-DACL 4300 Goodfellow Blvd. St. Louis, MO 63120-1798	1	Cdr, USATECOM ATTN: AMSTE-TD
		3	Cdr, CRDEC, AMCCOM ATTN: SMCCR-RSP-A SMCCR-MU SMCCR-MSI
		1	Dir, VLAMO ATTN: AMSLC-VL-D

<u>No. of</u> <u>Copies</u>	<u>Organization</u>	<u>No. of</u> <u>Copies</u>	<u>Organization</u>
10	C.I.A. OIR/DB/Standard GE47 HQ Washington, DC 20505	1	Office of the Asst Dep Dir of Defense Live Fire Testing ATTN: COL L. Stanford The Pentagon, Room 3E1060 Washington, DC 20301
1	HQDA (DAMI-FIT, COL Everson) WASH DC 20310-1001	2	OSD OUSD (A) ODDDRE (T&E/LFT) ATTN: Albert E. Rainis James O'Bryon The Pentagon, Room 3E1060 Washington, DC 20301-3110
1	HQDA (DAMO-ZD, Mr. Riente) The Pentagon, Rm 3A538 WASH DC 20310-0410	1	American Defense Preparedness Association (ADPA) ATTN: Bill King 1700 N. Moore Street, #900 Arlington, VA 22209-1942
1	HQDA (SARD-TN, LTC Fejfar) The Pentagon, Rm 3E360 WASH DC 20310	9	Defense Advanced Research Projects Agency ATTN: Mr. B. Bandy Dr. R. Kahn Dr. C. Kelly Mr. P. Losleben Dr. J. Lupo Mr. F. Patten Dr. Reynolds Mr. S. Squires COL J. Thorpe 1400 Wilson Boulevard Arlington, VA 22209
1	HQDA (Limres Study Group, Shirley D. Ford) The Pentagon, Room 1B929 WASH DC 20310	2	Central Intelligence Agency ATTN: ORD/PERD (Ray Cwiklinski) (Tom Kennedy) Washington, DC 20505
1	Office of the Assistant Secretary of the Army (Research, Development, and Acquisition) ATTN: LTG Cianciolo, Military Deputy Washington, DC 20310-0100	1	Central Intelligence Agency ATTN: ORD (Jim Fahnestock) Washington, DC 20505
1	Office of the Secretary of the Army (Research, Development, and Acquisition) ATTN: MG Beltson, Deputy for Systems Management Washington, DC 20310-0103	1	Central Intelligence Agency ATTN: ORD (Marvin P. Hartzler) Washington, DC 20505
1	Deputy Under Secretary of the Army for Operations Research ATTN: OUSA (Hon Walt Hollis) The Pentagon, Room 2E660 Washington, DC 20310-0102		
1	Office of the Deputy Director of Defense, R&E ATTN: Dr. William Snowden The Pentagon, Room 3D359 Washington, DC 20301		

<u>No. of Copies</u>	<u>Organization</u>
2	Central Intelligence Agency ATTN: OIA (Barbara A. Kroggel) (Monica McGuinn) Washington, DC 20505
1	Central Intelligence Agency ATTN: ORD (Peter Lew) 1820 N. Fort Myer Drive Arlington, VA 22209
1	Central Intelligence Agency ATTN: ORD (Donald Gorson) 1820 N. Fort Myer Drive Arlington, VA 22209
1	Chief of Naval Operations OP-03-C2 ATTN: CPT P.X. Rinn Rm 4D537, The Pentagon Washington, DC 20350-2000
1	Mr. Robert Gomez/OSWR PO Box 1925 Washington, DC 20013
1	Commander US Army Materiel Command ATTN: AMCDE-PI (Dan Marks) 5001 Eisenhower Avenue Alexandria, VA 22333-0001
1	Headquarters US Army Materiel Command ATTN: AMCDRA (R. Chait) 5001 Eisenhower Avenue Alexandria, VA 22333-0001
1	Commander US Army Materiel Command ATTN: AMCMT (John Kicak) 5001 Eisenhower Avenue Alexandria, VA 22333-0001
1	Commander US Army Materiel Command ATTN: AMCPD (Darold Griffin) 5001 Eisenhower Avenue Alexandria, VA 22333-0001

<u>No. of Copies</u>	<u>Organization</u>
1	Commander US Army Materiel Command ATTN: AMCPD-PM (Jim Sullivan) 5001 Eisenhower Avenue Alexandria, VA 22333-0001
2	Commander US Army Materiel Command ATTN: AMCPM-LOTA (Robert Hall) (MAJ Purdin) 5001 Eisenhower Avenue Alexandria, VA 22333-0001
1	Commander US Army Materiel Command ATTN: AMCPD-PT (Alan Elkins) 5001 Eisenhower Avenue Alexandria, VA 22333-0001
1	Commander US Army Laboratory Command ATTN: AMSLC-CT (K. Zastrow) 2800 Powder Mill Road Adelphi, MD 20783-1145
1	Commander US Army Laboratory Command ATTN: AMSLC-CG 2800 Powder Mill Road Adelphi, MD 20783-1145
1	Commander US Army Laboratory Command ATTN: SLCLT (LTC Marshall) 2800 Powder Mill Road Adelphi, MD 20783-1145
2	Commander US Army Laboratory Command ATTN: AMSLC-TP (J. Predham) (D. Smith) 2800 Powder Mill Road Adelphi, MD 20783-1145
1	Commander US Army Laboratory Command ATTN: SLCTO (Marcos Sola) 2800 Powder Mill Road Adelphi, MD 20783-1145

<u>No. of</u> <u>Copies</u>	<u>Organization</u>	<u>No. of</u> <u>Copies</u>	<u>Organization</u>
1	Commandant US Army Logistics Management College ATTN: AMXMC-LS-S (CPT(P) Stephen Parker) Ft. Lee, VA 23801	1	Commander US Army ARDEC ATTN: SMCAR-TDS (Vic Lindner) Picatinny Arsenal, NJ 07806-5000
1	Commander US Army Materials Technology Laboratory ATTN: SLCMT-ATL Watertown, MA 02172-0001	1	Commander US Army Aviation Systems Command ATTN: AMSAV-ES 4300 Goodfellow Blvd St Louis, MO 63120-1798
3	Director US Army Research Office ATTN: SLCRO-MA (Dr. J. Chandra) (Dr. K. Clark) (Dr. Wu) P.O. Box 12211 Research Triangle Park, NC 27709-2211	1	Commander US Army Aviation Systems Command ATTN: AMSAV-GT (C. Crawford) 4300 Goodfellow Blvd St. Louis, MO 63120-1798
1	Director US Army Survivability Management Office ATTN: SLCSM-C31 (H. J. Davis) 2800 Powder Mill Road Adelphi, MD 20783	2	Commander US Army Aviation Systems Command ATTN: AMSAV-NC (H. Law) (S. Meyer) 4300 Goodfellow Blvd St. Louis, MO 63120-1798
1	Director US Army Survivability Management Office ATTN: SLCSM-D (COL H. Head) 2800 Powder Mill Road Adelphi, MD 20783-1145	1	Commander Belvoir Research, Development and Engineering Center ATTN: STRBE-FC (Ash Patil) Fort Belvoir, VA 22060-5606
1	Commander US Army ARDEC ATTN: SMCAR-CCH-V (Paul H. Gemmill) Picatinny Arsenal, NJ 07806-5000	1	Commander Belvoir Research, Development and Engineering Center ATTN: STRBE-JDA (Melvin Goss) Fort Belvoir, VA 22060-5606
1	Commander US Army ARDEC ATTN: SMCAR-FSS-E (Jack Brooks) Picatinny Arsenal, NJ 07806-5000	1	Commander, USACECOM R&D Technical Library ATTN: ASQNC-ELC-I-T, Myer Center Fort Monmouth, NJ 07703-5000
1	Commander US Army ARDEC ATTN: SMCAR-TD (Jim Killen) Picatinny Arsenal, NJ 07806-5000	1	Director Center for Night Vision and Electro-Optics ATTN: AMSEL-RD-NV-V (John Palmer) Fort Belvoir, VA 22060-5677

<u>No. of</u> <u>Copies</u>	<u>Organization</u>	<u>No. of</u> <u>Copies</u>	<u>Organization</u>
1	Director Center for Night Vision and Electro-Optics ATTN: AMSEL-RD-NV-V (John Ho) Fort Belvoir, VA 22060-5677	1	Commander US Army Harry Diamond Laboratories ATTN: SLCHD-RT (Peter Johnson) 2800 Powder Mill Road Adelphi, MD 20783-1197
1	Director Center for Night Vision and Electro-Optics ATTN: AMSEL-RD-NV-D (Dr. R. Buser) Fort Belvoir, VA 22060-5677	1	Commander US Army INSCOM ATTN: IAOPS-SE-M (George Maxfield) Arlington Hall Station Arlington, VA 22212-5000
1	Commander US Army Foreign Science and Technology Center ATTN: AIFR (Bill Rich) 220 Seventh Street, NE Charlottesville, VA 22901-5396	2	Commander US Army Missile Command ATTN: AMSMI-RD-GC-T (R. Alongi) Redstone Arsenal, AL 35898-5000
4	Commander US Army Foreign Science and Technology Center ATTN: AIFRS (T. Walker) (D. Hardin) (R. Wittnebel) (John Aker) 220 Seventh Street, NE Charlottesville, VA 22901-5396	1	Commander US Army Missile Command ATTN: AMSMI-RD-SS-AT (Ed Vaughn) Redstone Arsenal, AL 35898-5000
2	Commander US Army Foreign Science and Technology Center ATTN: AIFRS (Gordon Spencer) (Dr. Steven Carter) 220 Seventh Street, NE Charlottesville, VA 22901-5396	1	Commander US Army Missile Command ATTN: AMSMI-YTSD (Glenn Allison) Redstone Arsenal, AL 35898-5070
1	Commander US Army Foreign Science and Technology Center ATTN: AIFRT (John Kosiewicz) 220 Seventh Street, NE Charlottesville, VA 22901-5396	1	Commander US Army Missile Command ATTN: AMSMI-REX (W. Pittman) Redstone Arsenal, AL 35898-5500
1	Commander US Army Foreign Science and Technology Center ATTN: AIFRE (S. Eitelman) 220 Seventh Street, NE Charlottesville, VA 22901-5396	1	Director US Army Missile and Space Intelligence Center ATTN: AIMS-RT (Pat Jordan) Redstone Arsenal, AL 35898-5500
		1	Director US Army Missile and Space Intelligence Center ATTN: AIMS-YLD (Vernon L. Stallcup) Redstone Arsenal, AL 35898-5500

<u>No. of Copies</u>	<u>Organization</u>
2	Director US Army Missile and Space Intelligence Center ATTN: AIMS-YRS, Thomas Blalock Pete Kirkland Redstone Arsenal, AL 35898-5500
2	Director US Army Missile and Space Intelligence Center ATTN: AIMS-YRT, Francis G. Cline Don A. Slaymaker Redstone Arsenal, AL 35898-5500
1	Director US Army Missile and Space Intelligence Center ATTN: Randy L. Smith Redstone Arsenal, AL 35898-5500
1	Commander US Army Natick R&D Center ATTN: STRNC-OI (Stephen A. Freitas) Natick, MA 01760
1	Commander US Army Tank-Automotive Command ATTN: AMCPM-BLK-III/COL Don Derrah Warren, MI 48397-5000
1	Commander US Army Tank-Automotive Command ATTN: AMSTA-CF (Dr. Orlicki) Warren, MI 48090
1	Commander US Army Tank-Automotive Command ATTN: AMSTA-CK (Newell) Warren, MI 48090
1	Commander US Army Tank-Automotive Command ATTN: AMSTA-CR (Mr. Wheelock) Warren, MI 48397-5000
1	Commander US Army Tank-Automotive Command ATTN: AMSTA-CV (COL Becking) Warren, MI 48397-5000

<u>No. of Copies</u>	<u>Organization</u>
2	Commander US Army Tank-Automotive Command ATTN: AMSTA-NKS (D. Cyaye) (J. Rowe) Warren, MI 48397-5000
2	Commander US Army Tank-Automotive Command ATTN: AMSTA-RG (R. Munt) (R. McClelland) Warren, MI 48397-5000
3	Commander US Army Tank-Automotive Command ATTN: AMSTA-RSC (John Bennett) (Wally Mick) Warren, MI 48397-5000
1	Commander US Army Tank-Automotive Command ATTN: AMSTA-RSK (Sam Goodman) Warren, MI 48090-5000
1	Commander US Army Tank-Automotive Command ATTN: AMSTA-VS (Brian Bonkosky) Warren, MI 48090-5000
6	Commander US Army Tank-Automotive Command ATTN: AMSTA-ZE (R. Asoklis) AMSTA-ZEA (C. Robinson) (R. Gonzalez) AMSTA-ZS (D. Rees) AMSTA-ZSS (J. Thompson) (J. Soltez) Warren, MI 48397-5000
1	Commander HQ, TRADOC ATTN: Asst Dep Chief of Staff for Combat Operations Fort Monroe, VA 23651-5000
2	Director HQ, TRAC RPD ATTN: ATRC-RP (COL Brinkley) ATRC-RPR (Mark W. Murray) Ft. Monroe, VA 23651-5143

No. of Copies	Organization	No. of Copies	Organization
1	Director US Army Cold Regions Research and Development Laboratory ATTN: Technical Director (Lewis Link) 72 Lyme Road Hanover, NH 03755	1	Director US Army Industrial Base Engineering Activity ATTN: AMXIB-MT Rock Island, IL 61299-7260
1	US Army Corps of Engineers Assistant Director Research and Development Directorate ATTN: Mr. B. Benn 20 Massachusetts Avenue, NW Washington, DC 20314-1000	1	Director US Army Industrial Base Engineering Activity ATTN: AMXIB-PS (Steve McGlone) Rock Island, IL 61299-7260
1	Commander US Army Operational Test and Evaluation Agency ATTN: MG Stephenson 4501 Ford Avenue Alexandria, VA 22302-1458	3	Director US Army Engineer Waterways Experiment Station ATTN: WESEN (Dr. V. LaGarde) (Mr. W. Grabau) WESEN-C (Mr. David Meeker) PO Box 631 Vicksburg, MS 39180-0631
1	Commander US Army Vulnerability Assessment Laboratory ATTN: SLCVA-CF (Gil Apodaca) White Sands Missile Range, NM 88002-5513	1	US Army Engineer Topographic Laboratories ATTN: Technical Director (W. Boge) Fort Belvoir, VA 22060-5546
1	Director TRAC-WSMR ATTN: ATRC-RD (McCoy) WSMR, NM 88002-5502	1	Commander US Army Operational Test and Evaluation Agency ATTN: LTC Gordon Crupper 4501 Ford Ave. #870 Alexandria, VA 22302-1435
2	US General Accounting Office Program Evaluation and Methodology Division ATTN: Robert G. Orwin Joseph Sonnefeld Room 5844 441 G Street, NW Washington, DC 20548	1	Lawrence Livermore National Laboratories PO Box 808 (L-3321) ATTN: Mark Wilkins Livermore, CA 94551
1	Director Office of the Deputy Under Secretary of the Army, Operations Research Study Program Management Agency ATTN: SFUS-SPM/E. Visco Washington, DC 20310-0102	3	Los Alamos National Laboratories ATTN: MS 985, Dean C. Nelson MS F600, Gary Tietgen MS G787, Terrence Phillips PO Box 1663 Los Alamos, NM 87545
		1	Los Alamos National Laboratories ATTN: MS F681, LTC Michael V. Ziehm USMC PO Box 1668 Los Alamos, NM 87545

<u>No. of Copies</u>	<u>Organization</u>
1	Sandia National Laboratories Department 913 ATTN: Ron Andreas Albuquerque, NM 87185-5800
1	Sandia National Laboratories Division 1611 ATTN: Tom James Albuquerque, NM 87185
1	Sandia National Laboratories Division 1623 ATTN: Larry Hostetler Albuquerque, NM 87185
1	Sandia National Laboratories ATTN: Gary W. Richter PO Box 969 Livermore, CA 94550
1	Commander US Naval Air Systems Command JTCG/AS Central Office ATTN: 5164J (LTC James B. Sebolka) Washington, DC 20361
1	Commander US Naval Ocean Systems Center ATTN: Earle G. Schweizer Code 000 San Diego, CA 92151-5000
4	Commander US Naval Surface Warfare Center ATTN: Gregory J. Budd James Ellis Barbara J. Harris Constance P. Rollins Code G13 Dahlgren, VA 22448-5000
2	Commander US Naval Weapons Center ATTN: Ed Patterson Dr. Helen Wang Code 3313 Bldg 1400, Room B17 China Lake, CA 93555

<u>No. of Copies</u>	<u>Organization</u>
1	Commander US Naval Weapons Center ATTN: Mark D. Alexander Code 3894 China Lake, CA 93556-6001
1	Commander US Naval Weapons Center ATTN: Melvin H. Keith Code 39104 China Lake, CA 93555
2	Commander US Naval Weapons Center ATTN: Tim Horton Dave Hall Code 3386 China Lake, CA 93555
1	Commander US Naval Weapons Center ATTN: Robert Cox Code 3917 China Lake, CA 93555-6001
1	Commander US Naval Civil Eng Laboratories ATTN: John M. Ferritto Code L53 Port Hueneme, CA 93043
1	Naval Postgraduate School ATTN: Dr. Michael J. Zyda Department of Computer Science Code 52 Monterey, CA 93943
1	Naval Postgraduate School Department of National Security ATTN: Dr. Joseph Sternberg Code 73 Monterey, CA 93943
1	Commander Intelligence Threat Analysis Center ATTN: PSD-GAS/John Bickle Washington Navy Yard Washington, DC 20374

No. of Copies	Organization	No. of Copies	Organization
1	Commander Intelligence Threat Analysis Center ATTN: Bill Davies Washington Navy Yard, Bldg 203 (Stop 314) Washington, DC 20374-2136	1	Commander USAF-HQ ATTN: AFTDEC/JT (COL Victor A. Kindurys) Kirtland AFB, NM 87117-7001
1	Commander Intelligence Threat Analysis Center ATTN: Ron Demeter Washington Navy Yard, B-213, Stop 314 Washington, DC 20374	2	Commander AFATL ATTN: AGA (Lawrence Jones) (Mickie Phipps) Eglin AFB, FL 32542-5434
1	Commander Intelligence Threat Analysis Center ATTN: Tim Finnegan Washington Navy Yard, B-213 Washington, DC 20374	1	Commander AFEWC ATTN: AFEWC/SAXE (Bod Eddy) Kelly AFB, TX 78243-5000
2	Commander Intelligence Threat Analysis Center Intell Image Prod Div ATTN: John Creighton Al Fuerst Washington Navy Yard, Bldg 213 (IAX-O-II) Washington, DC 20374	1	Commander AFWAL/AARA ATTN: Ed Zelano Wright-Patterson AFB, OH 45433
2	Commander David W. Taylor Naval Ship and Development Center ATTN: W. Conley J. Schot Bethesda, MD 20084	1	Commander AFWAL/FIES ATTN: James Hodges Sr. Wright-Patterson AFB, OH 45433-6523
1	Commander Eglin Air Force Base AD/ENL ATTN: Robert L. Stovall Eglin AFB, FL 32542	2	Commander AFWAL/MLTC ATTN: LT Robert Carringer Dave Judson Wright-Patterson AFB, OH 45433-6533
1	Commander USAF HQ ESD/PLEA Chief, Engineering and Test Division ATTN: Paul T. Courtoglous Hanscom AFB, MA 01730	1	Commander ASB/XRM ATTN: Gerald Bennett Wright-Patterson AFB, OH
		1	Commander WRDC/AARA ATTN: Michael L. Bryant Wright-Patterson AFB, OH 45433
		1	Commander FTD/SDMBA ATTN: Charles Darnell Wright-Patterson AFB, OH 45433

<u>No. of</u> <u>Copies</u>	<u>Organization</u>	<u>No. of</u> <u>Copies</u>	<u>Organization</u>
1	Commander FTD/SDMBU ATTN: Kevin Nelson Wright-Patterson AFB, OH 45433	1	Commander AD/ENY ATTN: Dr. Stewart W. Turner Director of Engineering Analysis Eglin AFB, FL 32542-5000
1	Commander FTD/SQDRA ATTN: Greg Koesters Wright-Patterson AFB, OH 45433-6508	2	Commander AD/ENYW ATTN: 2LT Michael Ferguson Jim Richardson Eglin AFB, FL 32542-5000
1	Commander FTD ATTN: Tom Reinhardt Wright-Patterson AFB, OH 45433	1	Commander Air Force Armament Laboratory ATTN: AFATL/DLY (James B. Flint) Eglin AFB, FL 32542-5000
1	Commander FTD/SCRS ATTN: Amy Fox Schalle Wright-Patterson AFB, OH 45433	4	Commander US Army FSTC ATTN: Greg Crawford David P. Lutz Suzanne Hall Charles Hutson 220 Seventh Avenue Charlottesville, VA 22901-5396
1	Commander FTD/SDJEO ATTN: Robert Schalle Wright-Patterson AFB, OH 45433		
1	Commander FTD/SDAEA ATTN: Joe Sugrue Wright-Patterson AFB, OH 45433	1	Commander US Army FSTC/CA3 ATTN: Scott Mingledorff 220 Seventh Avenue Charlottesville, VA 22901-5396
1	Commander AFWAL/AARA ATTN: Vincent Velten Wright-Patterson AFB, OH 45433	1	Commander US Army FSTC (UK) ATTN: MAJ Nigel Williams 220 Seventh Avenue Charlottesville, VA 22901-5396
1	Commander FTD/SQDRA ATTN: Larry E. Wright Wright-Patterson AFB, OH 45433	1	Commander US Army FSTC ATTN: Dr. Tim Small 220 Seventh Avenue Charlottesville, VA 22901-5396
1	Commander AD/CZL ATTN: James M. Heard Eglin AFB, FL 32542-5000	1	Defense Intelligence Agency ATTN: DB-6E3 (Jay Hagler) Washington, DC 20340-6763

No. of Copies	Organization	No. of Copies	Organization
6	Institute for Defense Analyses (IDA) ATTN: Mr. Irwin A. Kaufman Mr. Arthur O. Kresse Mr. Arthur Stein Dr. Lowell Tonnessen Mr. Benjamin W. Turner Ms. Sylvia L. Waller 1801 N. Beauregard Street Alexandria, VA 22311	1	AFELM, The Rand Corporation ATTN: Library-D 1700 Main Street Santa Monica, CA 90406
1	Institute for Defense Analyses ATTN: Carl F. Kossack 1005 Athens Way Sun City, FL 33570	2	Air Force Wright Aeronautical Labs ATTN: CDJ, CPT Jost CDJ, Joseph Faison Wright-Patterson AFB, OH 45433-6523
1	Department of Commerce National Institute of Standards and Technology Manufacturing Systems Group ATTN: B. Smith Washington, DC 20234	1	Alliant Computer Company ATTN: David Micciche 1 Monarch Drive Littleton, MA 01460
1	AAI Corporation ATTN: H. W. Schuette PO Box 126 Hunt Valley, MD 21030-0126	1	Alliston Gas Turbine Division of GM ATTN: Michael Swift PO Box 420, SC S22B Indianapolis, IN 46260-0420
1	ABEX Research Center ATTN: Dr. Michael J. Normandia 65 Valley Road Mahwah, NJ 07430	1	Aluminum Company of America ATTN: Charles Wood Alcoa Technical Center Alcoa Center, PA 15069
1	Adelman Associates ATTN: Herbert S. Weintraub 291 North Bernardo Avenue Mountain View, CA 94014-5205	1	ANSER ATTN: James W. McNulty 1215 Jefferson Davis Highway Arlington, VA 22202
1	The Armed Forces Communications and Electronics Association ATTN: Kirby Lamar, BG(Ret) 4400 Fair Lakes Court Fairfax, VA 22033-3899	1	ARC C-500 ATTN: John H. Bucher Modena Road Coatesville, PA 19320
2	Aero Corporation ATTN: David S. Eccles Gregg Snyder P.O. Box 92957, M4/913 Los Angeles, CA 90009	1	Armament Systems, Inc. ATTN: Gerard Zeller P.O. Box 158 211 West Bel Air Avenue Aberdeen, MD 21001
		1	Armored Vehicle Technologies ATTN: Coda M. Edwards PO Box 2057 Warren, MI 48090

No. of Copies	Organization
1	ASI Sytems, International ATTN: Dr. Michael Stamatelatos 3319 Lone Jack Road Encinitas, CA 92024
1	Auburn University Electrical Engineering Department ATTN: Dr. Thomas Shompert Auburn University, AL 36849
1	A.W. Bayer and Associates ATTN: Albert W. Bayer, President Marina City Club 4333 Admiralty Way Marina del Rey, CA 90292-5469
1	Battelle Research Laboratory Columbus Division 505 King Avenue Columbus, Ohio 43201-2693
1	Battelle Research Laboratory ATTN: Bernard J. Tullington 1300 N. 17th Street, Suite 1520 Arlington, VA 22209
1	The BDM Corporation ATTN: Edwin J. Dorchak 7915 Jones Branch Drive McLean, VA 22102-3396
1	The BDM Corporation ATTN: Fred J. Michel 1300 N. 17th Street Arlington, VA 22209
1	Bell Helicopter, Textron ATTN: Jack R. Johnson PO Box 482 Fort Worth, TX 76101
3	BMV, Division of Harsco ATTN: William J. Wagner, Jr. Ronald W. Jenkins Ed Magalski PO Box 1512 York, PA 17404

No. of Copies	Organization
1	Board on Army Science and Technology National Research Council Room MH 280 2101 Constitution Avenue, NW Washington, DC 20418
2	Boeing Aerospace ATTN: Dr. Robert Chiavetta Dr. John Kuras Mail Stop 8K17 P.O. Box 3999 Seattle, WA 98124-2499
2	Boeing Corporation ATTN: MS 33-04, Robert Bristow MS 48-88, Wayne Hammond PO Box 3707 Seattle, WA 98124-2207
1	Boeing Vertol Company A Division of Boeing Co. ATTN: MS P30-27, John E. Lyons PO Box 16858 Philadelphia, PA 19142
1	Booz-Allen and Hamilton, Inc. ATTN: Dr. Richard B. Benjamin Suite 131, 4141 Colonel Glenn Hwy. Dayton, OH 45431
1	Booz-Allen and Hamilton, Inc. ATTN: Jay A. Lobb 200 E. Big Beaver Rd. Troy, MI 48053
1	Booz-Allen and Hamilton, Inc. ATTN: Lee F. Mallett 1300 N. 17th Street, Suite 1610 Rosslyn, VA 22209
2	Booz-Allen and Hamilton, Inc. ATTN: John M. Vice WRDC/FIVS/SURVIAC Bldg 45, Area B Wright-Patterson AFB, OH 45433-6553

<u>No. of Copies</u>	<u>Organization</u>	<u>No. of Copies</u>	<u>Organization</u>
1	John Brown Associates ATTN: Dr. John A. Brown PO Box 145 Berkeley Heights, NJ 07922-0145	2	Cypress International ATTN: August J. Caponecchi James Logan 1201 E. Abingdon Drive Alexandria, VA 22314
1	Chamberlain ATTN: Mark A. Sackett PO Box 2545 Waterloo, IA 50704	1	DATA Networks, Inc. ATTN: William E. Regan, Jr. President 288 Greenspring Station Brooklandville, MD 21022
1	Commander Combined Arms Combat Development ATTN: ATZL-CAP (LTC Morrison) Dir, Surv Task Force Ft. Leavenworth, KS 66027-5300	1	Datatec, Inc. ATTN: Donald E. Cudney President 326 Green Acres Fort Walton, FL 32548
1	Commander Combined Arms Combat Development ATTN: ATZL-HFM (Dwain Skelton) Ft. Leavenworth, KS 66027-5300	1	University of Dayton Graduate Engineering and Research Kettering Lab 262 ATTN: Dr. Gary Thiele, Director Dayton, OH 45469
1	Computer Sciences Corporation 200 Sparkman Drive Huntsville, AL 35805	1	Delco Systems Operation ATTN: John Steen 6767 Hollister Avenue, #P202 Goleta, CA 93117
3	Computervision Corporation ATTN: A. Bhide V. Geisberg R. Hillyard 201 Burlington Road Bedford, MA 01730	1	Denver Research Institute Target Vulnerability and Survivability Laboratory ATTN: Lawrence G. Ulyatt PO Box 10127 Denver, CO 80210
1	Cray Research, Inc. ATTN: William W. Kritlow 2130 Main Street, #280 Huntington Beach, CA 92648	1	Denver Research Institute University of Denver ATTN: Louis E. Smith University Park Denver, CO 80208
1	CRS Sirmine, Inc. ATTN: Dr. James C. Smith PO Box 22427 1177 West Loop South Houston, TX 77227	1	Dow Chemical, U.S.A ATTN: Dr. P. Richard Stoesser Contract R&D 1801 Building Midland, MI 48674-1801
1	CSC ATTN: Abner W. Lee 200 Sparkman Drive Huntsville, AL 35805		

<u>No. of Copies</u>	<u>Organization</u>
1	Drexel University ATTN: Dr. Pei Chi Chou College of Engineering Philadelphia, PA 19104
1	DuPont Company FPD ATTN: Dr. Oswald R. Bergmann B-1246, 1007 Market Street Wilmington, DE 19898
1	Dynamics Analysis and Test Associates ATTN: Dr. C. Thomas Savell 2231 Faraday Ave Suite 103 Carlsbad, CA 92008
1	E. I. Dupont TED FMC ATTN: Richard O. Myers Jr. Wilmington, DE 19898
1	Eichelberger Consulting Company ATTN: Dr. Robert Eichelberger President 409 West Catherine Street Bel Air, MD 21014
1	Electronic Warfare Associates, Inc. ATTN: William V. Chiaramonte 2071 Chain Bridge Road Vienna, VA 22180
1	Emprise, Ltd. ATTN: Bradshaw Armendt, Jr 201 Crafton Road Bel Air, MD 21014
8	Environmental Research Institute of Michigan ATTN: Mr. K. Augustyn Mr. Kozma Dr. I. La Haie Mr. R. Horvath Mr. Arnold Mr. E. Cobb Mr. B. Morey Mr. M. Bair PO Box 8618 Ann Arbor, MI 48107

<u>No. of Copies</u>	<u>Organization</u>
1	E-OIR Measurements, Inc. ATTN: Russ Moulton PO Box 3348, College Station Fredericksburg, VA 22402
1	ERIM ATTN: Stephen R. Stewart Exploitation Applications Department Image Processing Systems Division PO Box 8618 Ann Arbor, MI 48107-8618
1	USA ETL/LAG ATTN: Jim Campbell Bldg 2592, Room S16 Ft. Belvoir, VA 22060-5546
1	FMC Corporation ATTN: Sidney Kraus 1105 Coleman Ave, Box 1201 San Jose, CA 95108
3	FMC Corporation ATTN: Ronald S. Beck Martin Lim Jacob F. Yacoub 881 Martin Avenue Santa Clara, CA 95052
3	FMC Corporation Advanced Systems Center (ASC) ATTN: Edward Berry Scott L. Langlie Herb Theumer 1300 South Second Street PO Box 59043 Minneapolis, MN 55459
2	FMC Corporation Defense Systems Group ATTN: Robert Burt Dennis R. Nitschke 1115 Coleman Avenue San Jose, CA 95037
1	FMC Corporation Naval Systems Division (NSD) ATTN: MK-45, Randall Ellis Minneapolis, MN 55421

No. of Copies	Organization	No. of Copies	Organization
1	FMC Corporation Northern Ordnance Division ATTN: M3-11, Barry Brown 4800 East River Road Minneapolis, MN 55421	1	General Dynamics Land Systems ATTN: Robert Carter PO Box 1804 Warren, MI 48090
6	FMC Corporation Ordnance Engineering Division ATTN: H. Croft M. Hatcher L. House J. Jackson E. Maddox R. Musante 1105 Coleman Ave, Box 1201 San Jose, CA 95108	1	General Dynamics Land Systems ATTN: Dr. Paulus Kersten PO Box 1901 Warren, MI 48090
1	GE Aircraft Engines ATTN: Dr. Roger B. Dunn One Neumann Way, MD J185 Cincinnati, OH 45215-6301	1	General Dynamics Land Systems ATTN: William M. Mrdeza PO Box 2045 Warren, MI 48090
1	General Atomics ATTN: Chester J. Everline, Staff Engineer P.O. Box 85608 San Diego, CA 92138-5608	5	General Dynamics Land Systems ATTN: Richard Auyer Otto Renius N. S. Sridharan Dean R. Loftin Dr. Phil Lett PO Box 2074 Warren, MI 48090-2074
1	General Dynamics ATTN: Dr. Fred Cleveland P.O. Box 748 Mail Zone 5965 Ft. Worth, TX 76101	3	General Motors Corporation Research Laboratories ATTN: J. Boyse J. Joyce R. Sarraga Warren, MI 48090
3	General Dynamics ATTN: MZ-4362112, Robert Carter MZ-4362029, Jim Graciano MZ-4362055, Gary Jackman 38500 Mound Sterling Heights, MI 48310	1	General Motors Corporation Military Vehicles Operations Combat Vehicle Center ATTN: Dr. John A. MacBain PO Box 420 Mail Code 01 Indianapolis, IN 46206-0420
3	General Dynamics Corporation ATTN: MZ-2650, Dave Bergman MZ-2860, John Romanko MZ-2844, Cynthia Waters PO Box 748 Ft. Worth, TX 76101-0748	1	Gettysburg College Box 405 Gettysburg, PA 17325
		1	Grumman Aerospace Corporation Research and Development Center ATTN: Dr. Robert T. Brown, Senior Research Scientist Bethpage, NY 11714

<u>No. of</u> <u>Copies</u>	<u>Organization</u>
1	GTRI-RAIL-MAD ATTN: Mr. Joe Bradley CRB 577 Atlanta, GA 30332
1	Honeywell ATTN: Hatem Nasr Systems and Research Center 3660 Technology Drive PO Box 1361 Minneapolis, MN 55418
1	Honeywell ATTN: Fred J. Parduhn 7225 Northland Drive Brooklyn Park, MN 55428
2	Honeywell, Inc. ATTN: Raymond H. Burg Laura C. Dillway MN38-4000 10400 Yellow Circle Drive Minnetonka, MN 55343
2	INEL/EG&G Engineer Lab ATTN: Ray Berry M. Marx Hintze PO Box 1625 Idaho Falls, ID 83451
1	Interactive Computer Graphics Center Rensselaer Polytechnic Inst. ATTN: M. Wozny Troy, NY 12181
1	International Development Corporation ATTN: Trevor O. Jones 18400 Shelburne Road Shaker Heights, OH 44118
1	ISAT ATTN: Roderick Briggs 1305 Duke Street Alexandria, VA 22314

<u>No. of</u> <u>Copies</u>	<u>Organization</u>
1	Jet Propulsion Laboratory California Institute of Technology ATTN: D. Lewis 4800 Oak Grove Drive Pasadena, CA 91109
1	Kaman Sciences Corporation ATTN: Timothy S. Pendergrass 600 Boulevard South, Suite 208 Huntsville, AL 35802
1	Ketron, Inc. ATTN: Robert S. Bennett 696 Fairmont Avenue Towsontown Center Towson, MD 21204
1	Keweenaw Research Center Michigan Technological University ATTN: Bill Reynolds Houghton, MI 49931
1	Lanxido Armor Products ATTN: Dr. Robert A. Wolffe Tralee Industrial Park Newark, DE 19711
2	Lincoln Laboratory MIT ATTN: Dr. Robert Shin Dr. Chuck Burt P.O. Box 73 Lexington, MA 02173
3	Lincoln Laboratory MIT Surveillance Systems Group ATTN: R. Barnes G. Knittel J. Kong 244 Wood Street Lexington, MA 02173-0073
1	Lockheed Corporation ATTN: R. C. Smith PO Box 551 Burbank, CA 91520

<u>No. of Copies</u>	<u>Organization</u>	<u>No. of Copies</u>	<u>Organization</u>
3	Lockheed-California Company ATTN: C. A. Burton R. J. Ricci M. Steinberg Burbank, CA 91520	1	Maxwell Laboratories, Inc. ATTN: Dr. Michael Holland 8888 Balboa Avenue San Diego, CA 92123-1506
2	Lockheed-Georgia Company ATTN: Ottis F. Teuton J. Tulkoff Dept. 72-91, Zone 419 Marietta, GA 30063	1	McDonnell Douglas Astronautic ATTN: Nikolai A. Louie 5301 Bolsa Avenue Huntington Beach, CA 92647
1	Logistics Management Institute ATTN: Edward D. Simms Jr. 6400 Goldsboro Road Bethesda, MD 20817-5886	1	McDonnell Douglas, Inc. ATTN: David Hamilton PO Box 516 St. Louis, MO 63166
1	Los Alamos Technical Associates, Inc. ATTN: John S. Daly 6501 Americas Parkway, #900 Albuquerque, NM 87110	1	McDonnell Douglas, Inc. ATTN: Alan R. Parker 3855 Lakewood Blvd., MC 35-18 Long Beach, CA 90846
1	LTV Aerospace and Defense Company ATTN: MS 194-51, Mike Logan P.O. Box 655907 Dallas, TX 75265-5907	1	Memex Corporation ATTN: Charles S. Smith 91 Belleau Ave. Atherton, CA 94025
1	LTV Aerospace and Defense Company ATTN: Daniel M. Reedy P.O. Box 655907 Dallas, TX 75265-5907	1	Micro Electronics of North Carolina ATTN: Gershon Kedem PO Box 12889 Research Triangle Park, NC 07709
3	Martin Marietta Aerospace ATTN: MP-113, Dan Dorfman MP-433, Richard S. Dowd MP-243, Thomas C. D'Isepo PO Box 555837 Orlando, FL 32855-5837	1	MIT ATTN: Dr. S. Benton RE15-416 Cambridge, MA 02139
3	Mathematical Applications Group, Inc. ATTN: M. Cohen R. Goldstein H. Steinberg 3 Westchester Plaza Elmsford, NY 10523	5	The MITRE Corporation ATTN: Edward C. Brady, Vice President Dr. Nicklas Gramenopoulos Gordon J. MacDonald Dr. Narayana Srinivasan Norman W. Huddy 7525 Colshire Drive McLean, VA 22102-3184
		1	NASA-Ames Research Center ATTN: Dr. Alex Woo Mail Stop 227-2 Moffett Field, CA 94035

No. of Copies	Organization	No. of Copies	Organization
1	NASA-Ames Research Center ATTN: Leroy Presley Mail Stop 227-4 Moffett Field, CA 94035	1	Princeton University Mathematics Department Fine Hall Washington Road ATTN: John Tukey Princeton, NJ 08544-1000
1	NAVIR DEVCON ATTN: Frank Wenograd Code 6043 Walminstor, PA 18974	1	PRI, Inc. ATTN: W. Bushell Building E4435, Second Floor Edgewood Area-APG, MD 21010
1	North Aircraft ATTN: Dr. Athanosis Varvatsis Mail Zone 3622/84 1 Northrop Ave Hawthorne, CA 90250	1	RGB Associates, Inc. ATTN: R. Barakat Box B Wayland, MA 01778
1	Northrop Corporation Research and Technology Center ATTN: James R. Reis One Research Park Palos Verdes Peninsula, CA 90274	1	Rockwell International Corporation ATTN: Dr. H. Bran Tran P.O. Box 92098 Department 113/GB01 Los Angeles, CA 90009
1	Norton Company ATTN: Ronald K. Bart 1 New Bond Street Worcester, MA 01606-2698	1	Rockwell International Corporation ATTN: Keith R. Rathjen, Vice President 3370 Miraloma Avenue (031-HA01) Anaheim, CA 92803-3105
1	The Oceanus Company ATTN: RADM Robert H. Gormley, (Ret) PO Box 7069 Menlo Park, CA 94026	1	Rome Air Development Center ATTN: RADC/IRRE, Peter J. Costianes Griffis Air Force Base, NY 13441-5700
1	Oklahoma State University College of Engineering, Architecture and Technology ATTN: Thomas M. Browder, Jr. PO Box 1925 Eglin AFB, FL 32542	1	Rome Air Development Center RADC/OCTM ATTN: Edward Starczewski Building 106 Griffis Air Force Base, NY 13441-5700
1	Pacific Scientific/Htl Division ATTN: Robert F. Aldrich 1800 Highland Avenue Duarte, CA 91010	1	S-Cubed ATTN: Michael S. Lancaster 1800 Diagonal Road, Suite 420 Alexandria, VA 22314
1	Perceptronics, Inc. ATTN: Dean R. Loftin 21111 Erwin Street Woodland Hills, CA 91367		

<u>No. of Copies</u>	<u>Organization</u>
1	Sachs/Freeman Associates, Inc. ATTN: Donald W. Lynch Senior Research Physicist 205 Yoakum Parkway, #511 Alexandria, VA 22304
1	SAIC ATTN: Dr. Alan J. Toepfer 2109 Air Park Drive, SE Albuquerque, NM 87106
1	SAIC ATTN: John H. McNeilly, Senior Scientist 1710 Goodridge Drive McLean, VA 22102
2	SAIC ATTN: Terry Keller Robert Turner Suite 200 1010 Woodman Drive Dayton, OH 45432
1	SAIC ATTN: David R. Garfinkle Malibu Canyon Business Park 26679 W. Agoura Road, Suite 200 Calabasas, CA 91302
1	Sidwell-Ross and Associates, Inc. ATTN: LTG Marion C. Ross, (USA Ret) Executive Vice President PO Box 88531 Atlanta, GA 30338
1	Sigma Research Inc. ATTN: Dr. Richard Bossi 4014 Hampton Way Kent, WA 98032
1	Simula, Inc. ATTN: Joseph W. Coltman 10016 South 51st Street Phoenix, AZ 85044

<u>No. of Copies</u>	<u>Organization</u>
1	SimTech ATTN: Dr. Annie V. Saylor 3307 Bob Wallace Ave., Suite 4 Huntsville, AL 35807
1	Alan Smolen and Associates, Inc. ATTN: Alan Smolen, President One Cynthia Court Palm Coast, FL 32027-8172
3	Southwest Research Institute ATTN: Martin Goland Alex B. Wenzel Patrick H. Zabel 6220 Culebra Road San Antonio, TX 78238
3	Sparta, Inc. ATTN: David M. McKinley Robert E. O'Connor Karen M. Rooney 4901 Corporate Drive Huntsville, AL 35805-6201
1	SRI International ATTN: Donald R. Curran 333 Ravenswood Ave. Menlo Park, CA 94025
2	Star Laboratory, Stanford University ATTN: Dr. John F. Vesecky Dr. Joseph W. Goodman Electrical Engineering Department 233 Durand Building Stanford, CA 94305-4055
3	Structural Dynamics Research Corporation (SDRC) ATTN: R. Ard W. McClelland J. Osborn 2000 Eastman Drive Milford, OH 45150
1	Syracuse Research Group ATTN: Dr. Chung-Chi Cha Merrill Lane Syracuse, NY 13210

<u>No. of Copies</u>	<u>Organization</u>
1	System Planning Corporation ATTN: Ann Hafer 1500 Wilson Blvd Arlington, VA 22209
1	S-Cubed ATTN: Robert T. Sedgwick PO Box 1620 La Jolla, CA 92038-1620
2	TASC ATTN: Charles E. Clucus Darrell James 970 Mar-Walt Drive Ft. Walton Beach, FL 32548
1	TASC ATTN: Harry I. Nimon, Jr 1700 N. Moore Street, Suite 1220 Arlington, VA 22209
1	Technical Solutions, Inc ATTN: John R. Robbins P.O. Box 1148 Mesillia Park, NM 88047
1	Teledyne Brown Engineering ATTN: John W. Wolfsberger, Jr. Cummings Research Park 300 Sparkman Drive, NW PO Box 070007 Huntsville, AL 35807-7007
1	Tradeways, Ltd. ATTN: Joseph G. Gorski, President 307F Maple Avenue West Vienna, VA 22180
1	Ultramet ATTN: Dr. Jacob J. Stiglich 12173 Montague Street Pacoima, CA 91331
1	United Technologies Corporation Advanced Systems Division ATTN: Richard J. Holman 10180 Telesis Court San Diego, CA 92121

<u>No. of Copies</u>	<u>Organization</u>
1	University of Idaho Department of Civil Engineering ATTN: Dr. Dennis R. Horn Assistant Professor Moscow, ID 83843-4194
1	University of Illinois at Chicago Communications Laboratory ATTN: Dr. Wolfgang-M. Boerner PO Box 4348 M/C 154, 1141-SEO Chicago, IL 60680
1	University of Illinois at Urbana-Champaign Department of Civil Engineering and Environmental Studies ATTN: Dr. E. Downey Brill, Jr. 208 North Romine Urbana, IL 61801-2374
1	University of Illinois at Urbana-Champaign Department of Electrical and Computer Engineering ATTN: Dr. Shung-Wu Lee 1406 W. Green Urbana, IL 61801
1	The Johns Hopkins University Applied Physics Laboratory ATTN: Jonathan Fluss Johns Hopkins Road Laurel, MD 20707
1	University of Nevada Environmental Research Center ATTN: Dr. Delbert S. Barth Senior Scientist Las Vegas, NV 89154-0001
1	University of North Carolina ATTN: Professor Henry Fuchs 208 New West Hall (035A) Chapel Hill, NC 27514

<u>No. of Copies</u>	<u>Organization</u>
3	Ohio State University Electroscience Laboratory ATTN: Dr. Ronald Marhefka Dr. Edward H. Newman Dr. Prasbhaker H. Pathak 1320 Kinnear Road Columbus, OH 43212
1	University of Rochester ATTN: Nicholas George College of Engineering and Applied Science Rochester, NY 14627
3	University of Utah Computer Science Department ATTN: R. Riesenfeld E. Cohen L. Knapp 3160 Merrill Engineering Bldg Salt Lake City, UT 84112
3	University of Washington 409 Department of Electrical Engineering, FT-10 ATTN: Dr. Irene Peden Dr. Akira Ishimaru Dr. Chi Ho Chan Seattle, WA 98105
1	Van Es Associates, Inc. ATTN: Dr. John D. Christie Vice President Suite 1407, 5202 Leesburg Pike Falls Church, VA 22041
1	Virginia Polytechnic Institute and State University Industrial Engineering Operations Research Department ATTN: Robert C. Williges 302 Whittemore Hall Blacksburg, VA 24061-8603
1	LTV Aircraft Products Group ATTN: Paul T. Chan, M/S 194-63 PO Box 655907 Dallas, TX 75265-5907

<u>No. of Copies</u>	<u>Organization</u>
1	XMCO, Inc. 460 Spring Park Pl #1500 Herndon, VA 22070-5215
1	XONTECH ATTN: John Dagostino 1701 N. Fort Myer Drive Suite 703 Arlington, VA 22209
1	Zernow Tech Services, Inc. ATTN: Dr. Louis Zernow 425 West Bonita, Suite 208 San Dimas, CA 91773
2	SURVICE Engineering ATTN: Jim Foulk George Lard 1003 Old Philadelphia Road Aberdeen, MD 21001
1	SURVICE Engineering ATTN: Edwin S. Wixson 3200 Carlisle Blvd., NE Suite 120 Albuquerque, NM 87100
2	Sverdrup Technology ATTN: Dr. Ralph Calhoun Bud Bruenning PO Box 1935 Eglin AFB, FL 32542
1	Georgia Technical Research Institute Systems and Technical Laboratory ATTN: Dr. Charles Watt 1770 Richardsons Road Smyrna, GA 30080
1	Georgia Institute of Technology ATTN: Dr. Richard Moore ECSL/EME ERB Building, Room 111 Atlanta, GA 30332

<u>No. of</u> <u>Copies</u>	<u>Organization</u>
1	Duke University Department of Computer Science, VLSI Raycasting ATTN: Dr. Gershon Kedem 236 North Building Durham, NC 27706
1	Virginia Technological Institute Electrical Engineering Department ATTN: Dr. David de Wolf 340 Whittemore Hall Blacksburg, VA 24061
1	Dr. Robert E. Ball, DA Consultant 642 Tyon Drive Monterey, CA 93940
1	Mr. Michael W. Bernhardt, DA Consultant Rt. 1, 12 Arthur Drive Hockessin, DE 19707
1	Mr. H. G. Bowen Jr., DA Consultant 408 Crown View Drive Alexandria, VA 22314-4804
1	Mr. Harvey E. Cale, DA Consultant 2561 Meadowbrook Lane Carson City, NV 89701-5726
1	Mr. Paul F. Carlson DA Consultant 11668 Tanglewood Drive Eden Prairie, MN 55347
1	Mr. Donald Gerson ORD 1820 N. Ft. Myer Drive Arlington, VA 22209
1	Mr. Abraham Golub DA Consultant 203 Yoakum Parkway, Apt 607 Alexandria, VA 22304

<u>No. of</u> <u>Copies</u>	<u>Organization</u>
1	Mr. Dave Hardison ASB Consultant 3807 Bent Branch Road Falls Church, VA 22041
1	Mr. Thomas Hafer, DARPA Consultant 1500 Wilson Blvd. 14th Floor Arlington, VA 22209
1	Mr. William M. Hubbard, ASB Consultant 613 Eastlake Drive Columbia, MO 65203
1	Mr. Charles E. Joachim, DA Consultant PO Box 631 Vicksburg, MS 39180
1	Dr. Edward R. Jones, DA Consultant 9881 Wild Deer Road St. Louis, MO 63124
1	MG Robert Kirwan (USA Ret), DA Consultant 10213 Grovewood Way Fairfax, VA 22032
1	US Army Field Artillery Board ATTN: Donald J. Krejcarek 4717 NE Macarthur Circle Lawton, OK 73511
1	Mr. Robert B. Kurtz, DA Consultant 542 Merwins Lane Fairfield, CT 06430-1920
1	Dr. Roy A. Lucht, Group M-B MS-J960 Los Alamos, NM 87545

No. of
Copies Organization

- 1 Mr. Donald F. Menne,
 Battelle Consultant
 617 Foxcroft Drive
 Bel Air, MD 21014
- 1 MG Peter G. Olenchuk (USA Ret),
 BAST Consultant
 6801 Baron Road
 McLean, VA 22101
- 1 Mr. Albert E. Papazoni,
 DA Consultant
 1600 Surrey Hill Drive
 Austin, TX 78746-7338
- 1 Harry Reed, Sr.
 Battelle Consultant
 138 Edmond St.
 Aberdeen, MD 21001
- 1 Mr. David L. Rigotti
 McClean Research Consultant
 127 Duncannon Road
 Bel Air, MD 21014
- 1 Dr. A. E. Schmidlin,
 DA Consultant
 28 Highview Road
 Caldwell, NJ 07006-5502
- 1 Mr. Charles S. Smith,
 BAST Consultant
 9 Doaks Lane
 Marblehead, Massachusetts 01945
- 1 Mr. Arthur Stein,
 BAST Consultant
 30 Chapel Woods Court
 Williamsville, NY 14221-1816
- 1 Dr. Dora Strother,
 ASB Consultant
 3616 Landy Lane
 Ft. Worth, TX 76118

Aberdeen Proving Ground

Dir, USAMSAA

ATTN:

AMXSY-A, W. Clifford
 J. Meredith
AMXSY-C, A. Reid
 W. Braerman
AMXSY-CR, M. Miller
AMXSY-CS, P. Beavers
 C. Cairns
 D. Frederick
AMXSY-G, J. Kramar
 G. Comstock
 E. Christman
 L. Kravitz
AMXSY-GA, W. Brooks
AMXSY-J, A. LaGrange
AMXSY-L, J. McCarthy
AMXSY-P, J. Cullum
AMXSY-RA, R. Scungio
 M. Smith

Cdr, USATECOM

ATTN:

AMSTE-CG, MG Akin
AMSTE-LFT, D. Gross
 R. Harrington
AMSTE-CG-LF
AMSTE-TC-C, R. Cozby

Dir, USAVLAMO

ATTN:

AMSLC-VL-CB, Mrs. Young
 Mr. Gross

INTENTIONALLY LEFT BLANK.

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. BRL Report Number BRL-MR-3880 Date of Report NOVEMBER 1990
2. Date Report Received _____
3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) _____

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) _____

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. _____

6. ~~General~~ Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) _____

CURRENT
ADDRESS

Name

Organization

Address

City, State, Zip Code

OLD
ADDRESS

Name

Organization

Address

City, State, Zip Code

7. If indicating a Change of Address or Address Correction, please provide the New or Correct Address in Block 6 above and the Old or Incorrect address below.

(Remove this sheet, fold as indicated, staple or tape closed, and mail.)

-----FOLD HERE-----

DEPARTMENT OF THE ARMY

Director

U.S. Army Ballistic Research Laboratory

ATTN: SLCBR-DD-T

Aberdeen Proving Ground, MD 21005-5066

OFFICIAL BUSINESS



NO POSTAGE
NECESSARY
IF MAILED
IN THE
UNITED STATES

BUSINESS REPLY MAIL
FIRST CLASS PERMIT No 0001, APG, MD

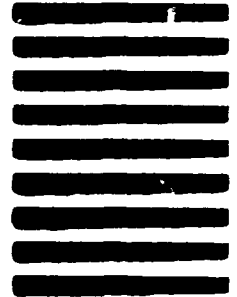
POSTAGE WILL BE PAID BY ADDRESSEE

Director

U.S. Army Ballistic Research Laboratory

ATTN: SLCBR-DD-T

Aberdeen Proving Ground, MD 21005-9989



-----FOLD HERE-----